AEDC-TR-84-30

Development of a Pressure Transducer for Usage in High-Temperature and Vibration Environments

Phase I: Feasibility Investigation

H. T. Liu
Flow Industries, Inc.
Research and Technology Division
21414 - 68th Avenue South
Kent, Washington 98032

and

G. Mauer and P. Zieve
Department of Mechanical Engineering
University of Washington

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Marshall K. Kingery

MARSHALL K. KINGERY
Directorate of Technology
Deputy for Operations

Approved for publication:

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Marion L. Laster

MARION L. LASTER
Director of Technology
Deputy for Operations

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The objective of the Phase I project is to determine the feasibility of developing a highly accurate, low-range pressure transducer that is suitable for measurement in environments where high vibrations, high temperatures and varying line pressures create problems for presently available transducers. The primary sensor is an elastic metal diaphragm that forms one plate of a capacitor; the other plate is fixed with respect to the diaphragm. An electronic circuit converts the diaphragm deflections, induced by a pressure force, into voltage variations that are then sampled by a microprocessor, which is to be developed in Phase II. Because of the small oscillating mass of the diaphragm, the transducer has a high natural frequency and is largely insensitive to externally induced vibrations. The simple configuration of the capacitive transducer is potentially applicable in extremely high-temperature environments. Furthermore, it can withstand very large overloads with appropriate installation of an overload stop between the two plates. In comparison with other types of pressure sensors, the capacitive transducer concept offers an unusual amount

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of design flexibility for a wide range of operational conditions. Phase I research demonstrated the feasibility of the capacitive transducer concept, as well as its capability to meet and potentially exceed all DoD requirements for transducer performance.

PREFACE

This DOD SBIR Phase I project is sponsored by the Department of the Air Force, Arnold Engineering Development Center (AEDC) under Contract No. F40600-83C0011. Mr. Frank T. Logan is the Technical Monitor. Phase I consists of a study to determine the feasibility of developing a differential pressure transducer for use in high-temperature and vibration environments. It includes six tasks:

Task 1. Design of the Capacitive Transducer

Task 2. Manufacture of Two Transducer Assemblies and a Test Stand

Task 3. Calibration and Testing of the Individual Components

Task 4. Calibration and Testing of the Completed Transducer

Task 5. Determination of the Frequency Response of the Transducer Assembly

Task 6. Preparation of the Final Report

All Phase I tasks were completed, and the results demonstrated the feasibility of the proposed development. As a result, a Phase II proposal was submitted to AEDC for further research and development leading to the construction of a prototype transducer to be used for the intended measurements. This report documents all the research and developmental work conducted in Phase I. Important findings indicating the success of the feasibility investigation are presented and discussed. Finally, recommendations for Phase II research and development are given.

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1. INTRODUCTION

Among all the product lines of pressure transducers there is no high-quality, low-range (1 and 2 psid) sensor suitable for air pressure measurements in high-temperature, vibration and line pressure environments typically encountered in turbojet engine testing. There is a need for an accurate and stable differential pressure transducer for measuring the pressure drop across a screen in the inlet plenum of an airbreathing cell at the AEDC Engine Test Facility. Under certain operational conditions, the accumulation of ice on the screen results in a significant pressure drop. When operating the Engine Test Facility, it is important to monitor that pressure drop as an indicator of the icing condition on the screen, so that corrective measures may be designed and implemented to remove the ice if necessary. A list of typical environmental conditions in one of the test cells (T-1) is provided in Section 2.

Applications of similar transducers for measuring absolute and differential pressure may be found in other test cells of the Engine Test Facility, where the environmental conditions are similar to those in the T-1 cell. Successful development of pressure transducers would open a wide range of other applications, e.g., in turbulent flow research and development, and in the automobile and aircraft industries:

- The transducer could be used in turbulence research to measure high-frequency pressure pulsations.
- The air pressure in combustion engine intakes and exhausts is subject to pulsations within a vibrating, high-temperature environment. The sensor could be useful both in combustion engine development and production quality control to accurately measure dynamic pressures or pressure differences.
- Because of its high sensitivity, the sensor can also be used to measure the dynamic pressure in pulsating gas or liquid flows in pipes in high temperature and pressure environments.

The objective of the Phase I study is to present sufficient information, gathered through literature review, theoretical analysis and laboratory experiments, to demonstrate the feasibility of the proposed capacitive pressure transducer.

Capacitive sensing is by no means a new idea. It has long been applied for measuring such physical quantities as displacements (Hitec Corporation, 1980; Garbini and Mauer, 1984; Kinsman, 1965), forces and pressures (e.g., load cells and pressure transducers made by many manufacturers), flow speed (Mauer, 1984) and acoustical signals (B & K, 1972; 1982). In other words, the method of capactive sensing is mature. The main reason that a capacitive pressure transducer has not been developed for high temperature and line pressure environments is the difficulty of maintaining the long-term stability of the sensing element and the electronic circuit under such adverse conditions. With the introduction of newly developed high-temperature materials, temperature-compensating circuitry and sensor fabrication techniques, these problems may be overcome or circumvented.

This report documents the research and developmental work performed in the Phase I study. Section 2 presents the concept of a capacitive pressure transducer and the design considerations for the proposed development. Section 3 describes the laboratory facilities in which the research and development was performed. The results of research and development are presented and discussed under Section 4. These results have positively demonstrated the feasibility of the proposed development of a capacitive pressure transducer. The important findings are summarized in Section 5, together with recommendations for major future research and development to be performed in Phase II.

A Phase II proposal has been submitted to AEDC for the continuation of this work. Phase II includes major research and developmental efforts toward the design and fabrication of a self-contained, microprocessor-controlled transducer assembly for use at the AEDC Engine Test Facility and for other engine testing and combustion related applications.

2. BACKGROUND

In this section the concept of a capacitive pressure transducer and its advantages over other pressure sensors are briefly described. DOD requirements specified by AEDC are presented, and the design considerations to meet or surpass these requirements are discussed.

2.1 Concept of a Capacitive Pressure Transducer

The primary sensing element of the pressure transducer is a capacitive sensor (Figure 1a), consisting of a fixed plate and a flexible diaphragm that is exposed to the pressure or pressure difference to be measured. The diaphragm is assumed to be thin and circular, so the standard diaphragm theory (outlined by Meirovitch, 1967) applies. The diaphragm displacement, which is proportional to the applied pressure, causes a variation of the capacitance C. The capacitance and the diaphragm displacement are represented by the simple relationship

$$C = \varepsilon\varepsilon_o A/d \tag{1}$$

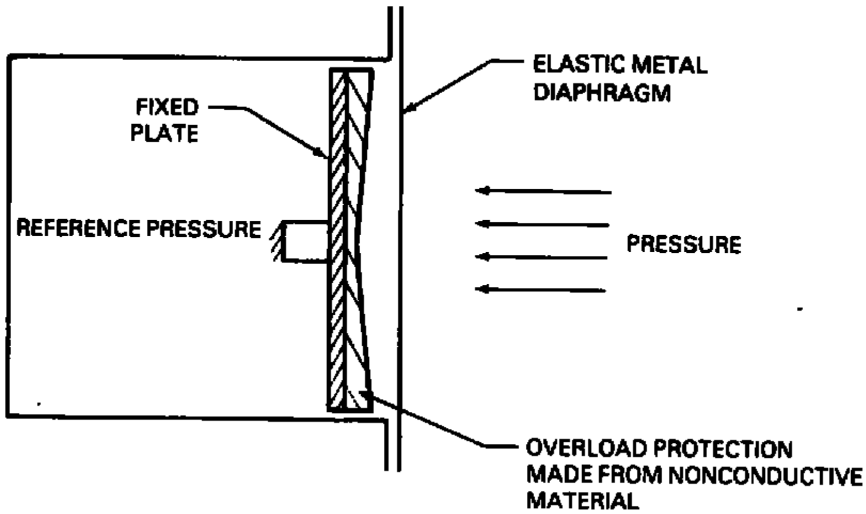
where ε and ε_o are the relative and absolute dielectric constants, A is the diaphragm area, and d is the diaphragm displacement.

The concept for a capacitive transducer suitable for measurement purposes has recently been developed by a group of researchers at the Department of Mechanical Engineering, University of Washington (Garbini and Mauer, 1984). In this transducer, the capacitance variations are used to modulate the frequency of an oscillator which operates at around 1 MHz. A phase-locked loop (PLL) circuit is used as a demodulator. The output voltage of the PLL circuit is sampled by a microprocessor or microcomputer, which corrects the measured signal according to the calibration curve and then displays or stores the results (Figure 1b).

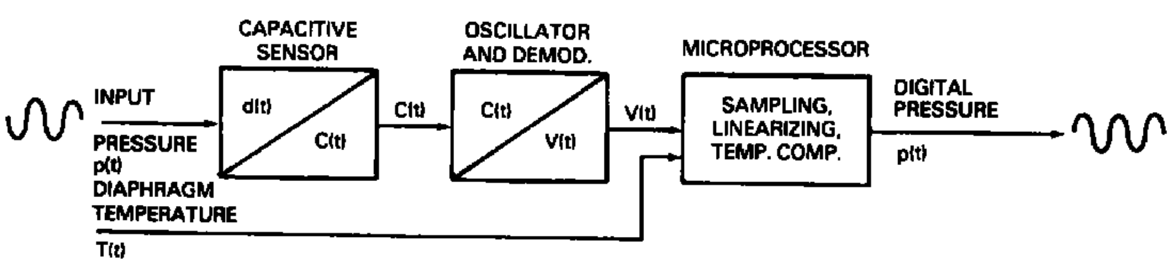
The proposed transducer, unlike presently available transducers, offers the following advantages:

- The capacitive sensor can be designed to have a very small oscillating mass. Consequently, the sensor has a fast transient response and a high natural frequency of at least 20 kHz. Higher natural frequencies can be achieved by simple design variations.

- Another benefit resulting from the small oscillatory mass is the fact that the transducer is largely insensitive to externally induced



a. Capacitive Pressure Sensor



b. Block Diagram of Pressure Measurements

Figure 1. Concept of a Capacitive Pressure Transducer

vibrations. The total diaphragm displacement is a function of the forces perpendicular to the diaphragm. These are the pressure force, which is given by resultant pressure times diaphragm area, and the vibration force, given by the oscillating diaphragm mass times acceleration.

- The transducer can be adapted for use in high-temperature environments by careful selection of the diaphragm material. Several materials such as Inconel, nickel, and ceramics are capable of operating in high temperatures. However, the choice of a different material would not affect the performance of the sensor. If necessary, a temperature sensor can be mounted next to the diaphragm to correct the pressure signal.

Like most pressure transducers, the capacitive sensor can be used to measure absolute pressure or pressure differences. While commercially available transducers that meet the requirements mentioned above do not yet exist, capacitive transducers for gauging small distances are marketed by several firms. As an example, Hitec Corporation (1980) quotes accuracies from 0.1 percent to 0.2 percent for its proximity sensors and, for some models, temperature ranges from kryogenic temperatures to 1500°F. The capacitive gauge prototypes developed at the University of Washington (Garbini and Mauer, 1984) also show accuracies better than 1 percent f.s.d. (full scale deflection) as well as excellent repeatability and long term stability.

2.2 Design Considerations

The design considerations are based on a set of DOD requirements provided by AEDC:

- Temperature Range - -10 to 225°F
- Velocity Range - 0 to 600 ft/s
- Frequency Response - 0 to 200 Hz
- Line Pressure Variation - 0 to 200 psia
- Vibration Environment - 10 G maximum with a vibrational frequency of 20 Hz to 2 kHz
- The pressure to be measured by this device is differential pressure

The above specifications correspond to the ambient conditions in the inlet plenum of an airbreathing cell (T-1) of the Engine Test Facility at AEDC. One of the intended applications for the pressure transducer under development is to measure and monitor the pressure drop across a screen in that plenum of T-1 cell. Under certain operating conditions, ice tends to form and accumulate on the screen, significantly increasing the pressure drop across the screen.

For efficient operation of the T-1 test cell, it is important to accurately correlate the pressure drop with the extent of the icing on the screen so that corrective measures may be designed and implemented. For operational convenience, the transducer developed for this purpose should be capable of operating for at least six months before a recalibration is required. The environmental conditions in other test cells are quite similar to the above specifications, with perhaps higher line pressure and temperatures in a few of them. Therefore, the goal is to develop a transducer with rated specifications at least matching those listed above, to significantly widen its applications under extremely adverse conditions.

In order to achieve the high natural frequency required by DOD, the primary sensing element of the capacitive transducer must be a thin prestressed elastic diaphragm. The theory of diaphragm deflections and vibrations, described in Meirovich (1967) and Timoshenko (1959), dictates that diaphragm prestress be high and that diaphragm diameter be as small as possible. On the other hand, the capacitance generated by the diaphragm and the fixed plate should be as large as possible, to ensure the best frequency stability in the oscillator circuit. Also, for good sensitivity, a small diaphragm deflection must generate the maximum change of capacitance. This is achieved by placing the fixed plate so close to the diaphragm that contact (current flow) is barely avoided when the largest pressure signal is applied.

To verify theoretical findings for their application to a capacitive pressure sensor, two capacitive microphone cartridges were selected and tested: the Bruel & Kjaer Type 4133 with a 1.2 cm diaphragm diameter and the Type 4136 with a 0.6-cm diaphragm. The test results are consistent with the theoretical predictions. Capacitive sensor parameters available from the manufacturer, including data on natural frequency, temperature coefficient and sensitivity to vibrations, were consistent with the experimental results.

3. LABORATORY FACILITIES

All research and development were conducted in FLOW's Fluid Mechanics Laboratory and in the laboratory of the Mechanical Engineering Department, University of Washington. This section describes the laboratory facilities used for the above work.

FLOW's Fluid Mechanics Laboratory is equipped for conducting experiments to determine a variety of fluid properties and flow characteristics. Only those facilities pertinent to the present research and development are described below.

3.1 On-Line Data Acquisition System

The laboratory is equipped with a minicomputer for on-line data acquisition and analysis. This system consists of a NOVA 800 minicomputer with a 32K core and peripheral equipment, which includes (i) two magnetic disk drives, an Iomec and a Diablo, each having a 2.5M word capacity, (ii) a Wang 9-track, 800-BPI magnetic-tape drive, (iii) a Houston Instrument DPI incremental plotter, (iv) a Versatec model 1100A electrostatic printer-plotter, (v) a Tektronix CRT and hardcopier unit, and (vi) a Teletype. In addition, the computer is equipped with floating-point, integer-multiply-divide, digital I/O and digital/analog conversion hardware for analog input data.

The signal conditioner has a total of 48 analog input channels. Each channel has three switchable low pass filters. Of these 48 channels, 32 have additional dc voltage offset. The maximum sampling rate is 250K per second. Recently, FLOW acquired a 16-channel microcomputer-controlled programmable signal conditioner manufactured by Datacon Electronics (Model PSC-16). Individual channels have the separate programmable functions of low-pass filtration (4 poles, 8 discrete settings), gain setting (0 to 25.5 with an increment of 0.1) and dc voltage offset (-10 to +10 volts with an increment of 80 mv). Once set, all these functions of individual channels may be loaded into memory and subsequently recalled. This programmable signal conditioner, instead of the older one, was used in the present investigation.

A set of computer programs is available for statistical and spectral analysis of the data. The spectrum is estimated by performing a fast-Fourier transformation of the auto- or cross-covariance function of a time series. Each time series is divided into eight segments of lengths 1/8N, where N equals 8192, the total number of points used for the spectral estimation. A sample of the spectrum is estimated from each of the eight segments, and these samples are then averaged to generate the mean spectrum. The spectrum is then smoothed by using a Parzen window. Therefore, the degree of freedom for the data is 30 and the standard error is estimated to be 26%. The 95% confidence limit for the spectrum (Jenkins and Watts, 1968) is (0.63S(f), 1.78S(f)) where S(f) is the spectral density. The 95% confidence limit is represented by an error bar in the corresponding figures presented later in this report.

3.2 Nicolet Digital Oscilloscope

The Nicolet 4094 digital oscilloscope consists of three main components: the mainframe, the Model 4562 plug-in and the XF-44/1 disk recorder. The mainframe includes a display memory, display screen and various controls to manipulate the display screen components. The controls feature horizontal and vertical expansion to x256, autocentering, choice of XY and XT displays, 16K word display memory which can be left intact or divided into halves or quarters, and multiple function abilities including arithmetic manipulations, electronic graticule, and pen recording outputs.

The Model 4562 plug-in includes two 12-bit, 500-nanosecond digitizers. Other plug-in features include: two high-impedance, differential amplifiers; single 16K word memory; single-ended or differential amplifiers; positive, negative or dual slope triggering; normal, pre- and post-trigger, and delayed trigger displays; a trigger view mode for setting up the triggering threshold; low-pass filtration, sweep and point averaging; etc.

The disk recorder transfers data onto the floppy diskette for storage. The stored data can be recalled at a later time for inspection on the screen. The diskette is divided into twenty individual records, each capable of storing either one (16K), two (8K), or four (4K) data groups. A set of 23 programs are available from the Stand Pak programs for statistical and waveform analysis of the signals stored on diskettes. For examples, there are programs to estimate the maximum and minimum, the rise time of a wave form, the area, and the average and rms values. Programs are also available for differentiation, integration, and inversion of the signals.

3.3 Special Apparatus

Two special apparatus were designed and assembled to determine the dynamic response of the capacitive pressure transducer under development. A dynamic test stand was constructed to determine the rise time of the transducer. This consists of a thin air jet chopped mechanically by a rotating slot wheel, which serves as a fast action on-off valve. The jet impinges onto a 0.38-mm hole drilled on an aluminum cap that covers the pressure sensor of the transducer. The transducer measures the total pressure of the jet which is chopped at very high frequency. To simulate the pressure drop across the screen in the inlet plenum of the T-1 test cell at the AEDC Engine Test Facility, a pipe flow system was constructed with several stainless steel screens and perforated plates installed.

Figure 2 shows the drawing of the setup of the dynamic test stand. The jet is formed by forcing air pressurized up to 100 psi through a small sapphire nozzle, which is secured in a holder housed in a stainless steel body. The diameter of the nozzle orifice is 0.12 cm. Upstream of the nozzle, there is a settling plenum designed to optimize the coherence of the jet. The nozzle assembly is a standard component of a FLOW Waternife™, a commercial product which generates a high-pressure (up to 55,000 psi) waterjet for cutting and drilling various materials.

As shown in the figure, the air jet is chopped mechanically by a rotating slot wheel (11.4 cm in diameter), which is mounted on a Dremel portable drill press equipped with a variable-speed drill motor (1000 to 8000 rpm). The slot wheel is placed between the air jet and the pressure transducer. Two quarter sections of the outside 1.3 cm of slot wheel are removed opposite to each other. The jet is centered between the inner and outer diameters of the wheel with the transducer directly below the air jet.

A pipe system was assembled to simulate the pressure drop across the screen at the inlet of the T-1 test cell at AEDC (Figure 3). Filtered high-pressure air up to 100 psi is fed into a steel pipe 1.6 cm in diameter. In the middle of the setup, two pipes are joined together. Sandwiched between the pipes are several stainless steel screens (30 meshes) and plates perforated with 0.1-cm diameter holes spaced by 0.26 cm apart (center-to-center). The differential pressure across the screens and plates is measured by two pressure transducers, one under development and the other a Micro Switch Model 142PC05D (see Section 3.7), as a calibrator with known characteristics, at two pressure taps upstream and downstream of the screens and plates. The Micro Switch transducer is a solid-state piezoresistive device with a relatively high response time, better than 1 ms. The number of screens and plates and the sizes of the

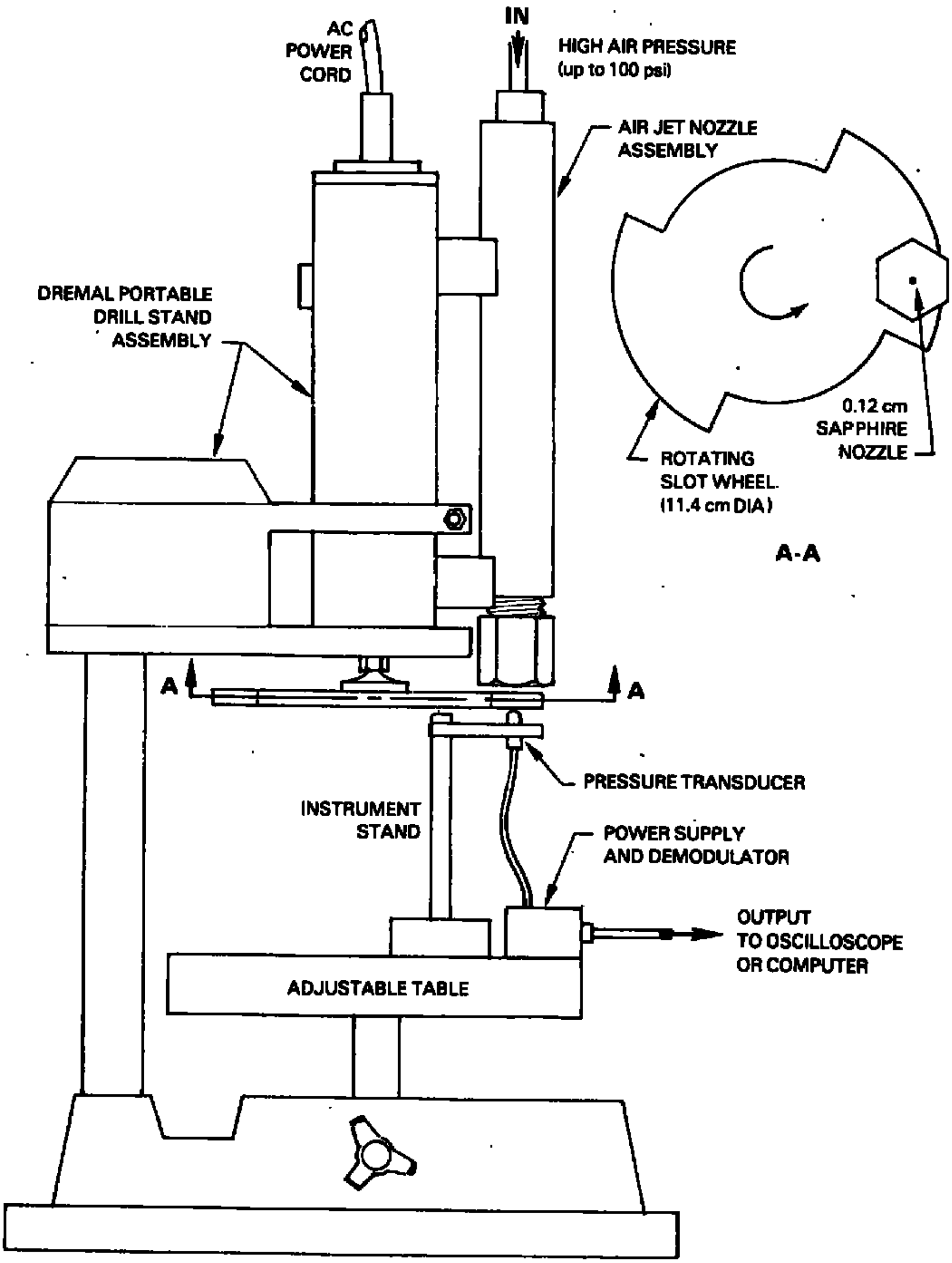


Figure 2. Setup for Dynamic Test of Pressure Transducer

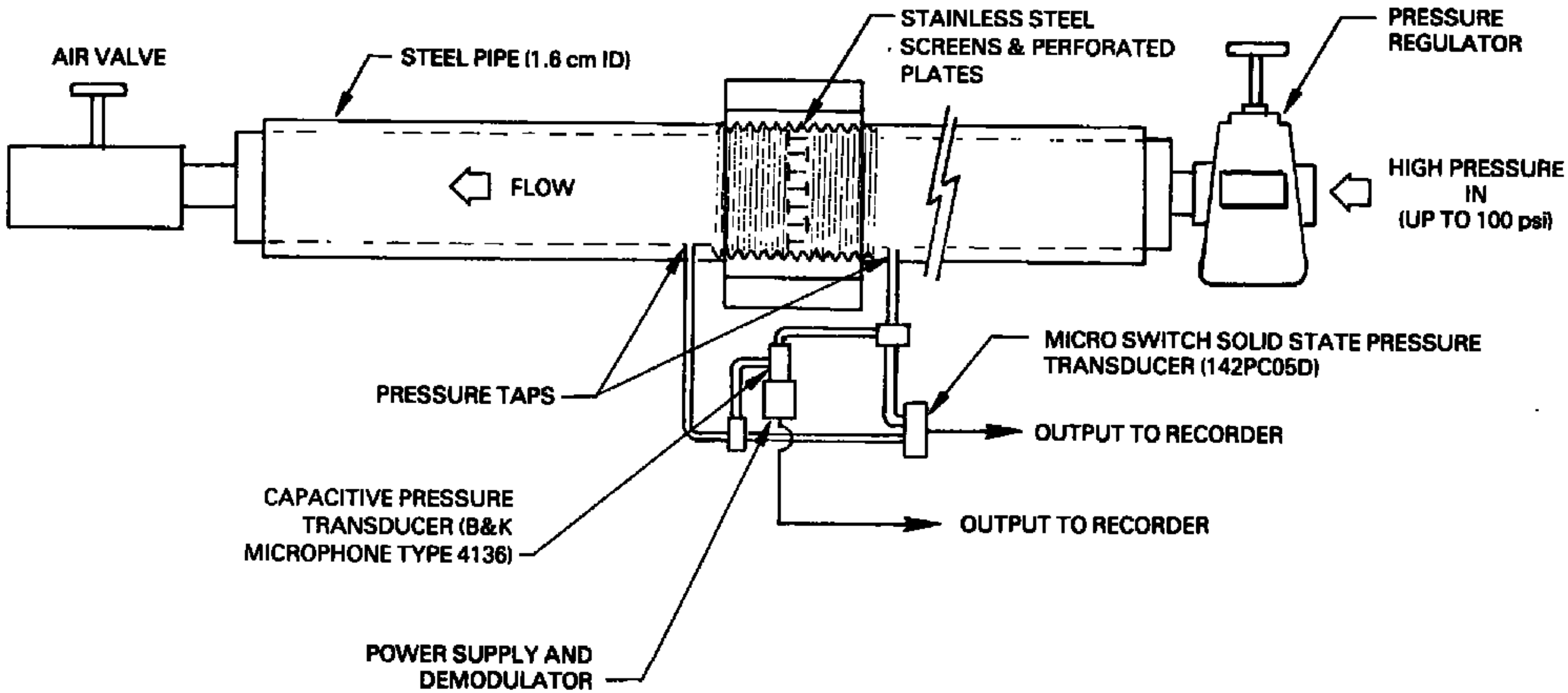


Figure 3. Pipe Flow Setup Simulating the Pressure Drop Across the Screen in the Inlet Plenum of an Airbreathing Test Cell

openings may vary to generate a suitable pressure drop across the screen with a relatively wide range of spectral components in both the frequency and wave-number domains. The steel pipe can be heated up easily to study the effect of elevated temperature on the transducer output.

3.4 Mechanical Shaker

A mechanical shaker (Ling Electronics Type 408) was used to test the capacitive sensor for sensitivity to vibrations. The shaker operates in a frequency range from 5 Hz to 9 kHz and can deliver forces up to 55 lb, creating accelerations up to 70 G. According to the specifications listed in Section 2.2, accelerations up to 14 G peak (10 G r.m.s.) were generated. A Kistler Model 808K piezoelectric accelerometer was used to measure the accelerations generated by the shaker. Both the accelerometer and the capacitive pressure sensor were mounted directly onto the shaker table (Figure 4). The calibrated output of the amplifier unit of the accelerometer is 10 mV/G.

3.5 Oven

A laboratory oven (Electric Hotpack Co., Model 35732) was used for the temperature tests. The oven is thermostatically controlled and operates in a range from 35 to 260°C.

3.6 Pressure Gauge

Three pressure gauges were used in the feasibility study. A Barocel precision pressure transducer (Datametrics, Inc.) with a full-scale pressure of 1000 torrs or 19.34 psi was used for static calibration (Section 4.3). A 5 psi diaphragm gauge (Marshalltown Instruments, Model G22702) with a 0.1 psi graduation was used to calibrate the pressure transducers prior to each experiments in the pipe flow system (Section 4.4.2). For the dynamic tests and the frequency-response tests (Section 4.3), a solid state piezoresistive, differential pressure gauge (Micro Switch, Model 142PC05D) was selected. This provided an independent set of base data by which to evaluate the performance of the transducer under development. The maximum differential pressure that can be measured with the Micro Switch gauge is 5 psi. According to literature furnished with the transducer, the calibration is practically linear and the rise time in response to a pressure pulse is better than 1 ms.

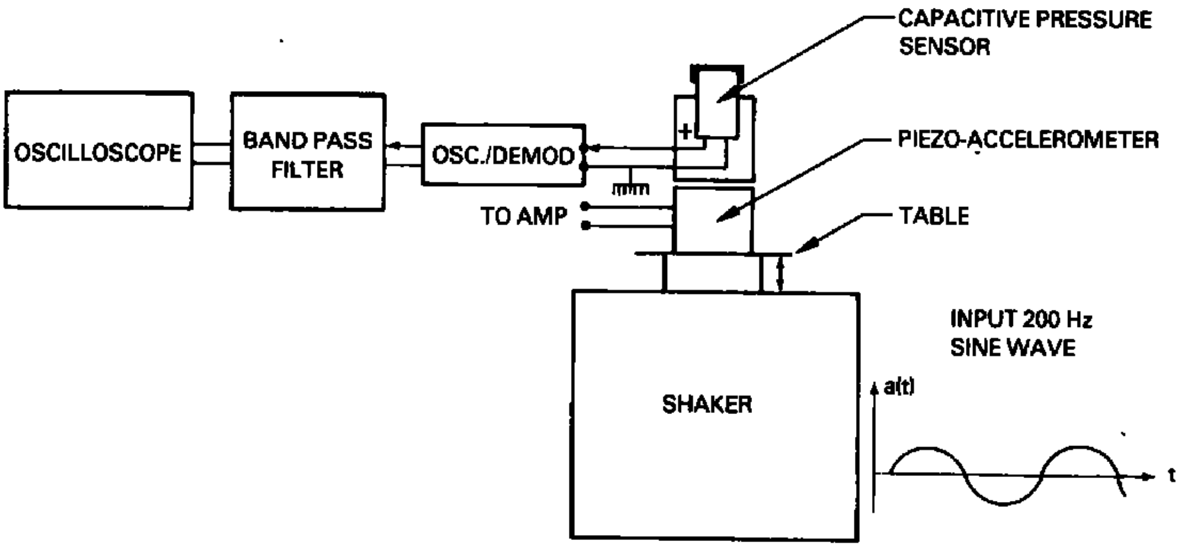


Figure 4. Schematic of a Vibration Test Stand

3.7 Other Equipment

The manufacturing automation laboratory at the University of Washington is a modern facility equipped for the development and testing of electronic instrumentation. Equipment available for this project included:

- Several dual channel Tektronix 5110 oscilloscopes, one Tektronix two-channel Type 468 digital storage oscilloscope
- Three Fluke 1700/2400 laboratory computers equipped for automated measurement and control tasks
- Computing and graphics facilities (PDP 11/44 computer system)
- A Fluke Type 1953A counter/timer for frequencies up to 10 GHz

4. RESULTS OF RESEARCH AND DEVELOPMENT

This section presents the results of the research and development conducted in Phase I to determine the feasibility of using a capacitive pressure transducer for the proposed measurements (see Section 2).

4.1 Selection of the Primary Sensors

Once the specifications and the intended measurements of the transducer were defined, one of the most critical steps was to select a primary sensor for the transducer that would meet or surpass the DOD requirements. Following the design considerations given in Section 2, a set of essential criteria was established for the primary sensor. Proper selection of the primary sensor was considered the key to the success of subsequent research and development, and of establishing the feasibility of the concept. Therefore a careful search was made to locate potentially applicable commercial products before designing and fabricating a new sensor. After screening and reviewing information obtained from manufacturers of pressure transducers and condensor microphones, two condenser microphone cartridges manufactured by Bruël & Kjaer (B & K Type 4136 and 4133) were found to be the most promising. The 0.6-cm diameter Type 4136 cartridge was especially suitable for use as the primary sensor for the transducer. Table 1 compares the required and rated specifications for the B & K Type 4136 cartridge. Other relevant specifications of the cartridges are given in a comprehensive master catalog (B & K, 1983) and a handbook (B & K, 1982). An in-depth discussion of the environmental effects on the cartridge is provided in Section 4.5.

It is clearly demonstrated in Table 1 and in the referenced literature that the specifications of the cartridge surpass most of the DOD requirements. With proper modifications of the cartridge, as discussed in the next subsection and Section 5, it is anticipated that the primary sensor will surpass all the DOD requirements. Therefore, the transducer under development has the potential for measurements in more adverse environments than that of the intended applications.

4.2 Modifications of Cartridge Configurations

The B & K cartridges are designed to measure ac acoustic pressure. Modifications of its configuration and redesign of the electronics are necessary to convert them into the primary sensor of the pressure transducer for the

Table 1. Comparison of Required and Rated Specifications

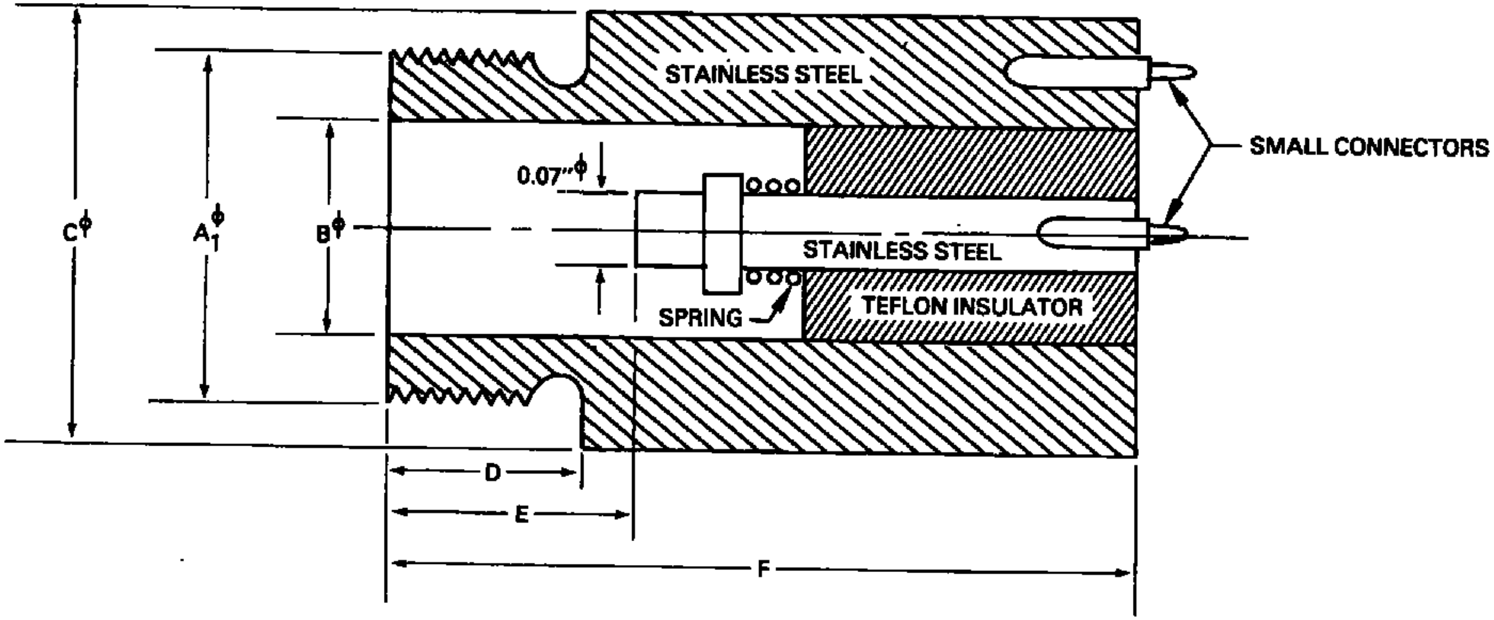
	DOD Specifications	Rated (B & K 4136)*
Temperature Range (°F)	-10 to 225	-58 to 302
Velocity Range (ft/s)	0 to 600	N/A
Frequency Response (Hz)	0 to 200	up to 70,000†
Line Pressure Variation (psia)	0 to 200	**
Vibrational Environment	10 G (20 Hz to 2 kHz)	less than 0.1% error for 10 G axial vibration
Maximum Differential Pressure (psid)	2	greater than 3

*From Bruel and Kjaer (1982).
†For ac signals only; modifications required for dc signals.
** No data available, but calibration has been made up to 147 psia on one side of the diaphragm, which is made of nickel about 5 μm thick.

intended measurements of dc pressure differentials. Consequently, two connectors were designed and fabricated for the Type 4133 and 4136 cartridges (Figure 5), and a sensor housing was built for the Type 4136 cartridge (Figure 6). The connectors are for hookups to the sensor power supply and to the frequency demodulator. The cartridge housing protects the diaphragm and provides high- and low-pressure ports connecting to the differential pressure source.

4.3 Electronic Circuits

Two electronic circuits were developed and tested to determine suitability for the transducer under development. These circuits used the principles of frequency and amplitude modulation (FM and AM), respectively. The circuits were evaluated for sensitivity, linearity, frequency response and temperature stability. Most of the static calibration and all the dynamic tests documented in this report were conducted with the FM circuit. The AM circuit was subsequently developed as an alternate to the FM circuit.



MEASURE	1/4" CONNECTOR	1/2" CONNECTOR
Aϕ	0.22 (60 thread)	0.46 - (60 threads/inch)
Bϕ	0.15	0.3
Cϕ	0.25	0.5
D	0.08	0.1
E	0.15	0.12
F	1.0	1.5

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Figure 5. Electrical Connectors for Microphone Cartridges

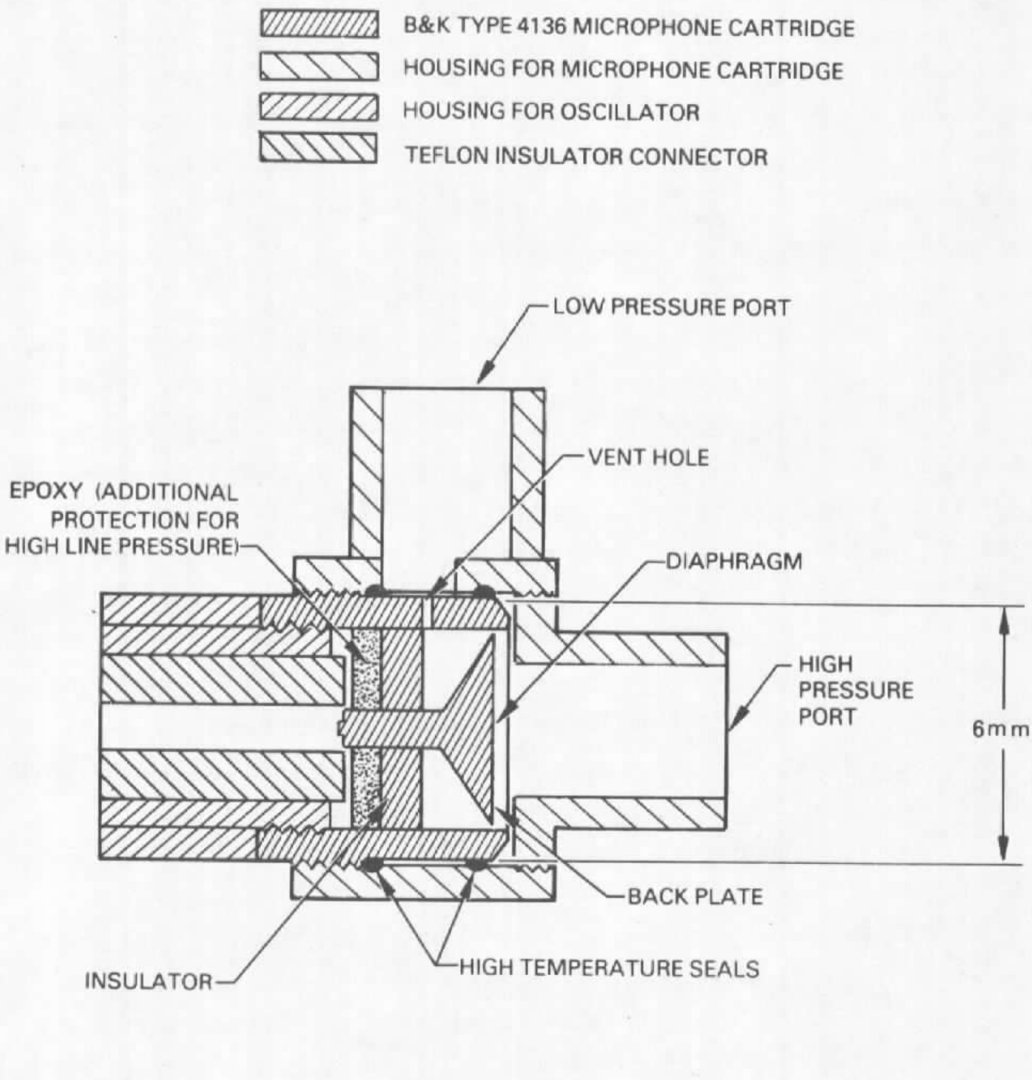


Figure 6. Housing for the B&K Type 4136 Cartridge

4.3.1 Frequency Modulated Circuit

The FM circuit is shown in Figure 7. A square wave oscillator was developed and built for use with the capacitance-based pressure transducer. A design goal for the oscillator is that the frequency should be optimally dependent on the value of probe capacitance. The square wave oscillator frequency will vary at twice the rate of a sine wave oscillator for the same variation in probe capacitance. This can be readily understood, since a square wave generator has a frequency law that is proportional to 1/RC, where R is the feedback resistance and C is the total system capacitance. A sine wave generator has a frequency law that is proportional to $1/\sqrt{LC}$, where L is the inductance.

The pressure transducer has a capacitance on the order of 10 pf, so the oscillator must be designed to function on extremely small current levels. It is desirable to minimize stray and constant capacitances, which decrease device sensitivity. The oscillator chosen employs a Schmidt trigger (bistable high-gain inverter) with a high-speed operational amplifier. An operational amplifier is required since the input current of the inverter while switching is greater than the charging current of the probe. In addition, an operational amplifier with a small offset current must be employed. Frequency information is extracted from the system through a high-impedance buffer so that the oscillator frequency will be dependent on probe capacitance only.

Figure 8 illustrates the approximate wave forms observed at several points around the oscillator feedback loop. An approximate 0.55 volt offset is employed across the operational amplifier to adjust the square wave duty cycle to 50%. The Schmidt trigger turns on and off when the input voltage goes below 0.85 volt and above 1.65 volt. Consequently, the input voltage must traverse 0.8 volts for each 1/2 cycle. The output of the Schmidt trigger is bistable, and jumps three volts upon switching. As can be seen in Figure 8, the output of the Schmidt trigger is a simple RC circuit. The voltage applied to the circuit at the beginning of each 1/2 cycle is:

$$(3 + 0.8)/2 \tag{2}$$

The RC charging equation yields the period for a 1/2 cycle:

$$0.8/1.9 = 1 - \exp(-t/RC) \tag{3}$$

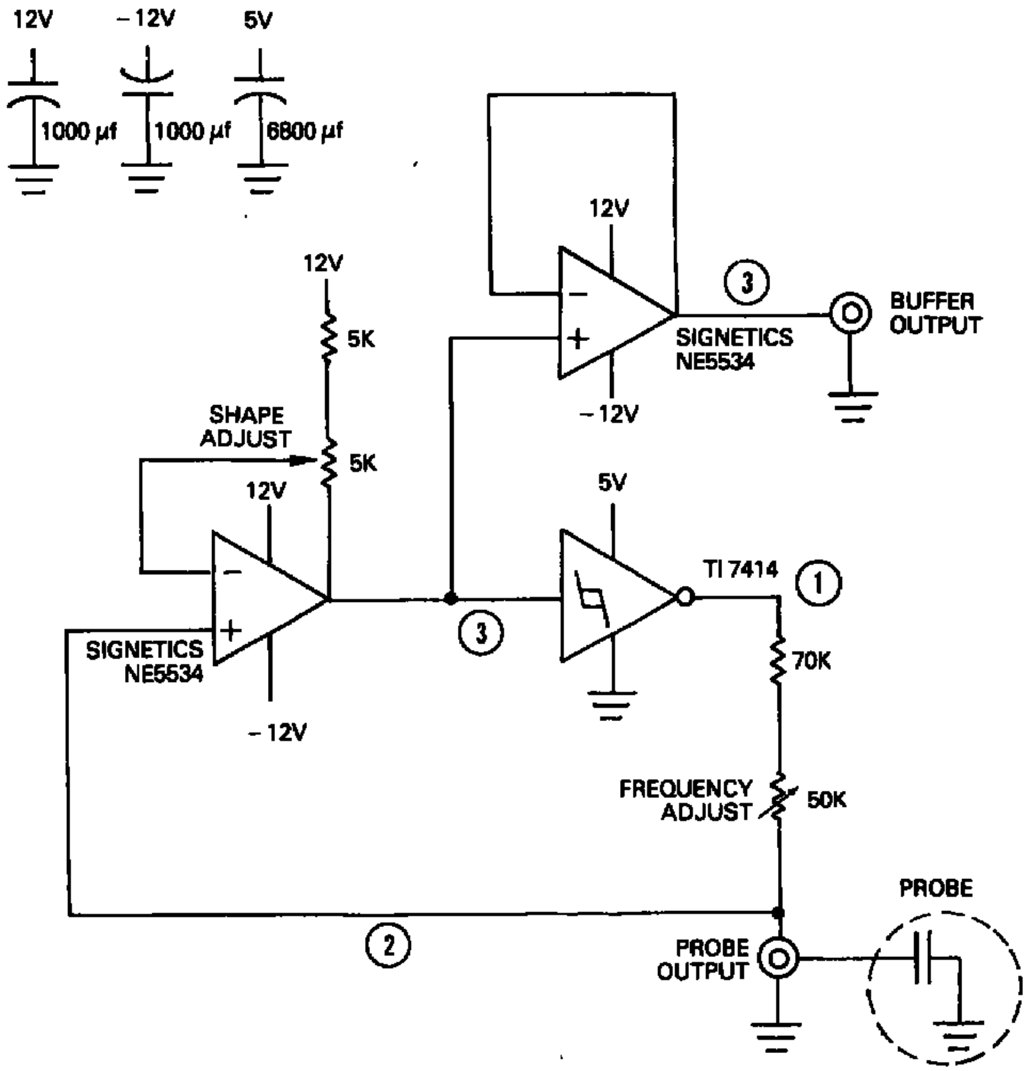


Figure 7. Frequency Modulated Circuit

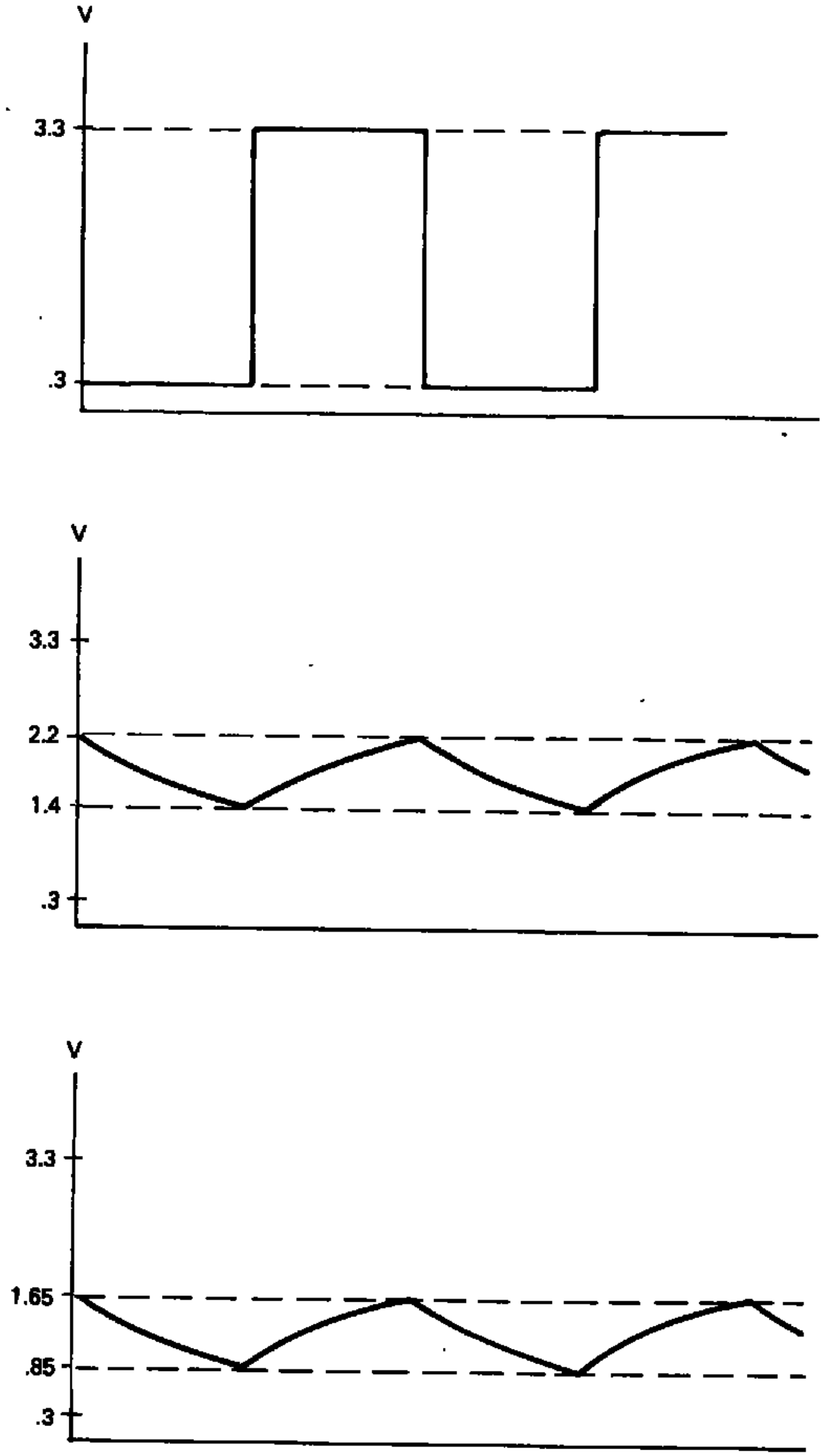


Figure 8. Approximate Wave Forms Observed Around the Oscillator Feedback Loop

Solving for t and doubling yields the period of a full cycle:

$$T = 1.093\ RC \tag{4}$$

The frequency equation is validated through varying the resistor and capacitor values by known amounts. After confidence is gained in the relationship, the output frequency can be employed to determine the values of system parameters.

Through this technique the stray capacitance of the circuitry is determined to be 5.5 pf. In addition, the 1/4" microphone at zero pressure has a capacitance of 6.3 pf. Frequency versus pressure data can be employed to determine the capacitance versus pressure relationship shown in Figure 9.

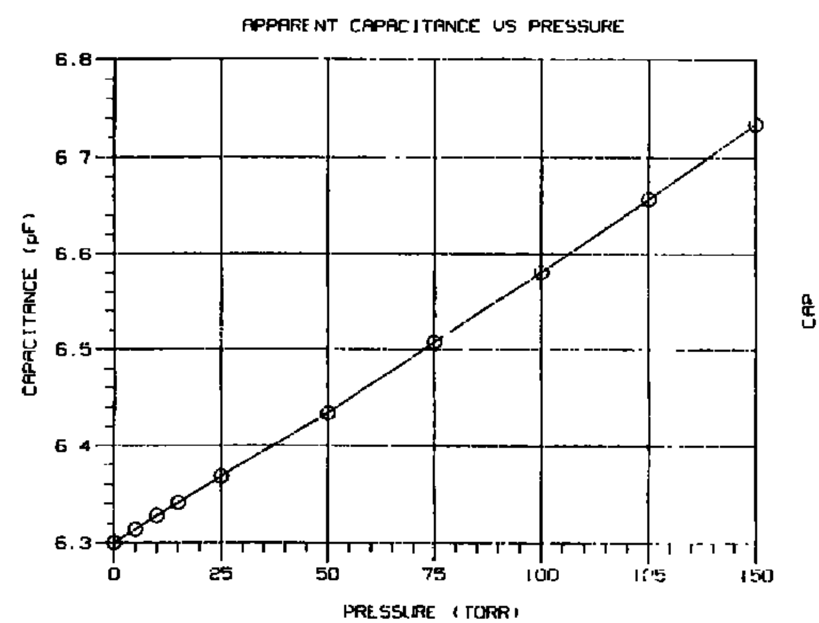


Figure 9. Capacitive Versus Pressure Relationship

The value of capacitance which should be employed in the above frequency relationship is:

$$C = C_{Microphone} + C_{Stray} \tag{5}$$

Note that the microphone capacitance increases by 0.43 pf when the pressure is raised to 150 Torr.

Figure 10 shows the phase-locked loop (PLL) demodulator circuit that was used for the dynamic measurements. Preliminary experimentation with fast dynamic pressure variations has shown that the PLL circuit is suitable for pressure frequency variations of 10 kHz and beyond.

A Barocel precision pressure transducer was employed to determine the static calibration curve of the capacitive pressure transducer and of the oscillator circuit. The Barocel pressure gauge is calibrated in torrs (1 torr = 0.01934 psi), and the maximum pressure difference used in the experiments was 150 torr (2.9 psi). Figures 11a and 11b show the recorded calibration curves using two oscillator frequencies at zero pressure difference. Figure 12 is the corresponding PLL voltage output calibration for the same condition as in Figure 11. All calibration curves were recorded with the Type 4136 microphone cartridge. From the three figures, we have demonstrated that the oscillator circuit may be optimally tuned to provide near linear outputs with pressure. The larger Type 4133 cartridge (1.2-cm in diameter) was used during the experimental oscillator design process, because it allows study of the influence of varying currents through the capacitance with respect to the overall circuit stability. However, this cartridge is not suitable for pressure differences above 1 psi.

4.3.2 Amplitude Modulated Circuit

The AM oscillator/demodulator circuit are shown in Figure 13a. An inductance in parallel is added to the capacitance from the pressure transducer, forming an LC resonant loop. This resonant circuit is driven by a crystal-controlled oscillator at a constant frequency near the LC resonant frequency. Variations of capacitance at the pressure transducer change the resonant frequency of the LC circuit. The peak voltage observed at the LC circuit is a measure of the capacitance variation. When dynamic pressure variations occur, the envelope of the peak voltage variations represents the capacitance and thus the pressure signal, which can be retrieved using a diode as a demodulator.

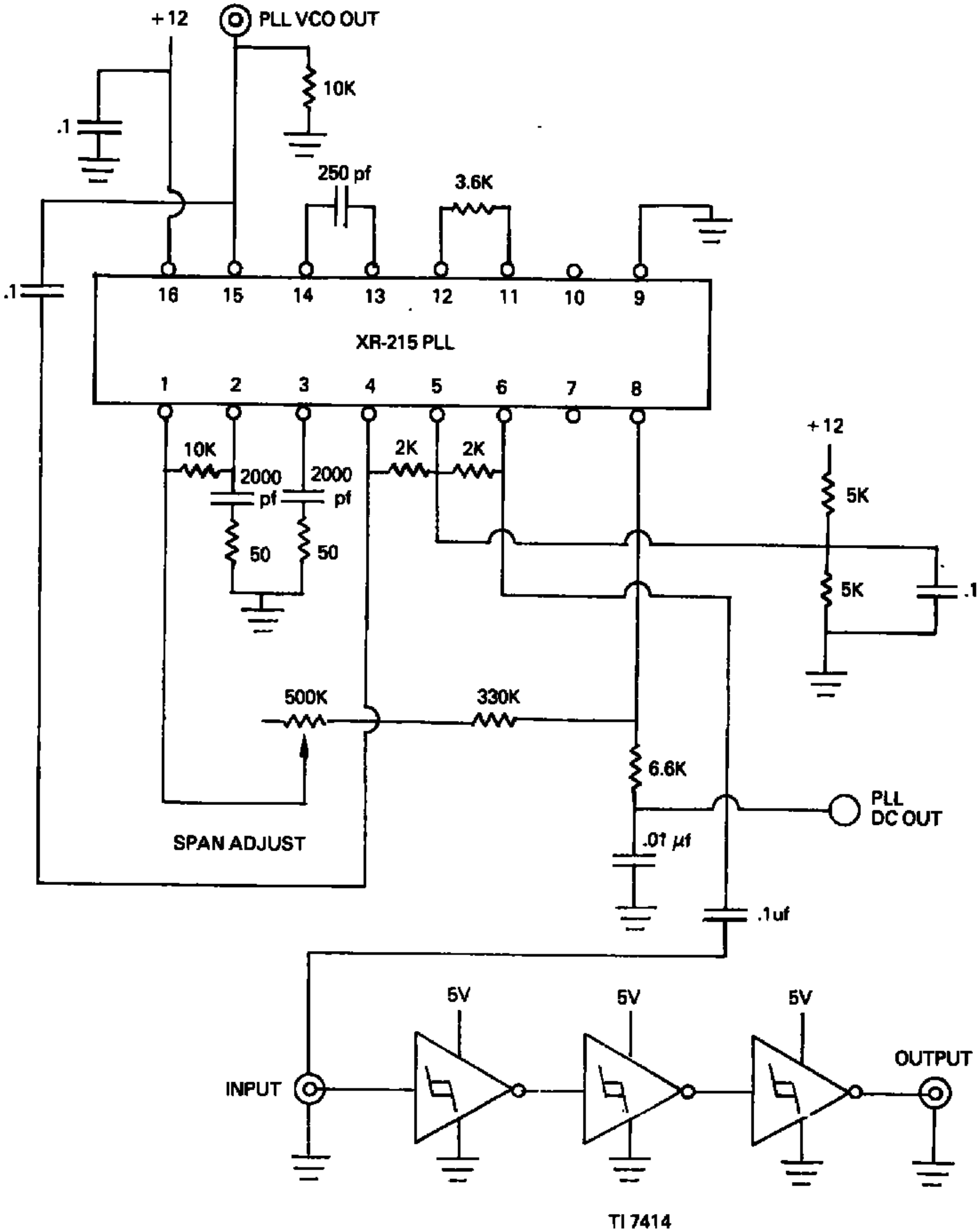
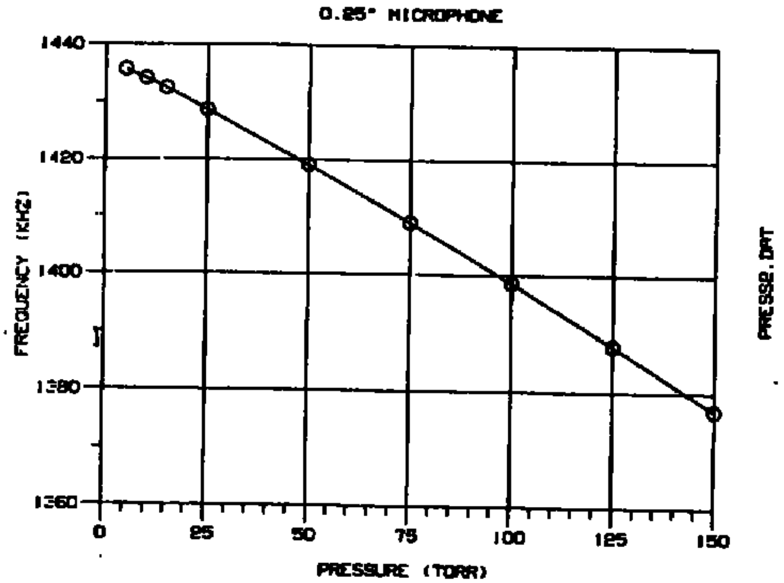
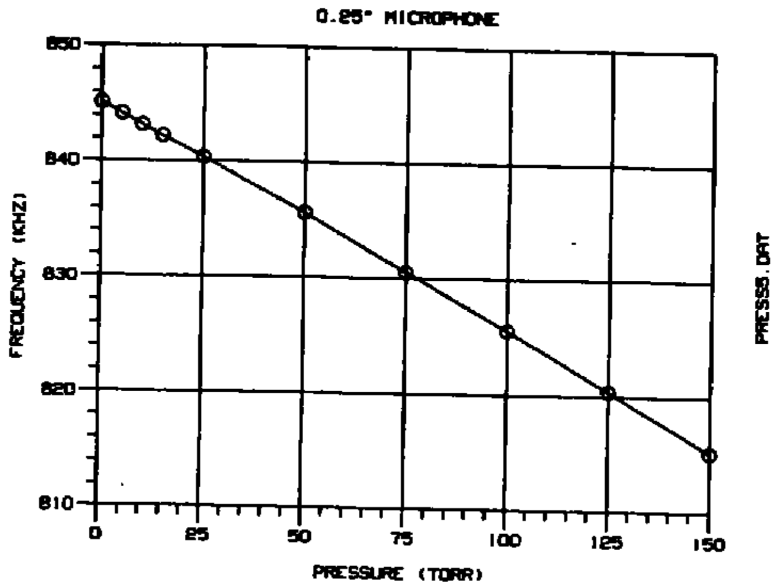


Figure 10. Phase-Locked Loop Demodulator Circuit



a. Resonant Frequency = 1.437 MHz



b. Resonant Frequency = 845 kHz

Figure 11. Static Calibrations of the Capacitive Pressure Transducer by the FM Circuit at Two Resonant Frequencies (Zero Pressure Difference)

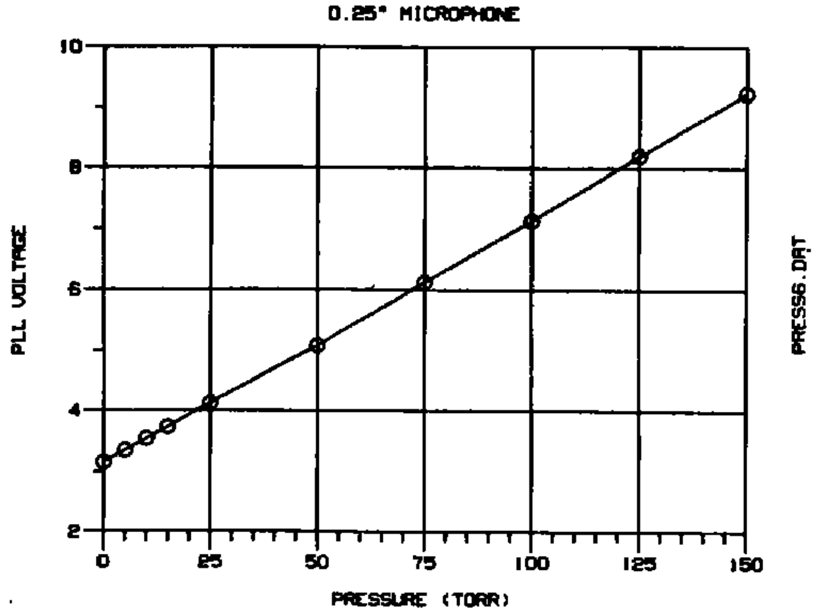


Figure 12. PPL Voltage Output Calibration

The main advantage of the amplitude-modulated capacitance detection circuit is its significantly higher stability as compared with the previously used FM-type oscillator. By using a temperature-stabilized, crystal-controlled oscillator as an input to the resonant LC circuit, temperature drift and frequency stability problems will be avoided as far as the electronic capacitance detection circuit is concerned.

When connected to the capacitive pressure transducer the circuit provides an electrical output signal proportional to pressure; as the transducer capacitance changes, the magnitude of the output waveform varies. Demodulation is achieved with a diode. Buffering is employed at both the input and output of the resonant circuit to optimize the response. At resonance, the amplitude of the LC element is ten times higher than the supply voltage.

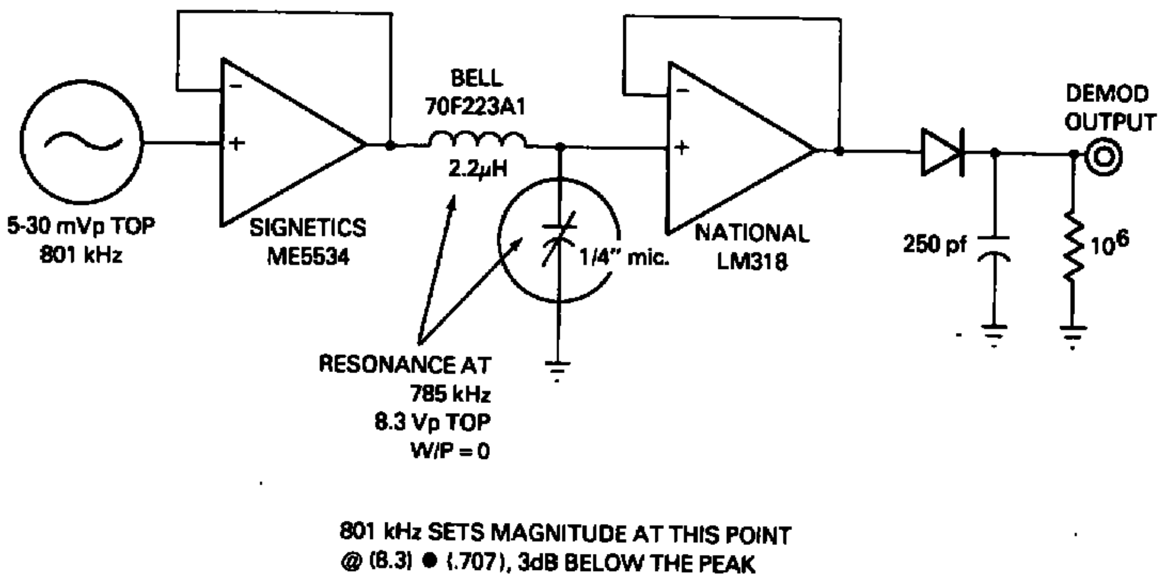


Figure 13a. Amplitude Modulated (AM) Oscillator/Demodulator Circuit

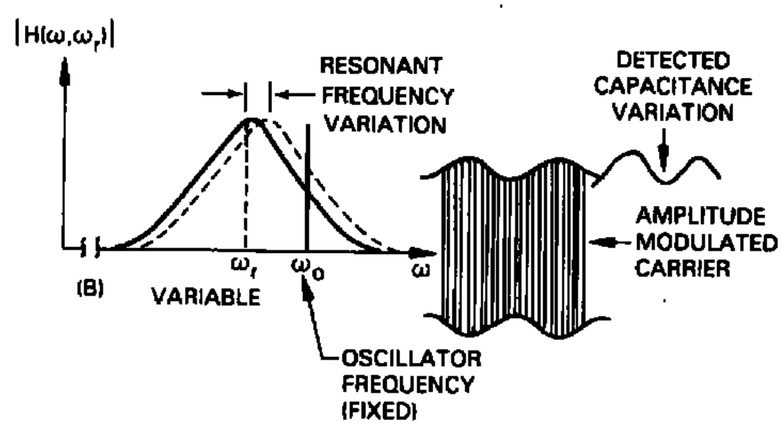


Figure 13b. Frequency Response of the LC Circuit and Amplitude Modulation

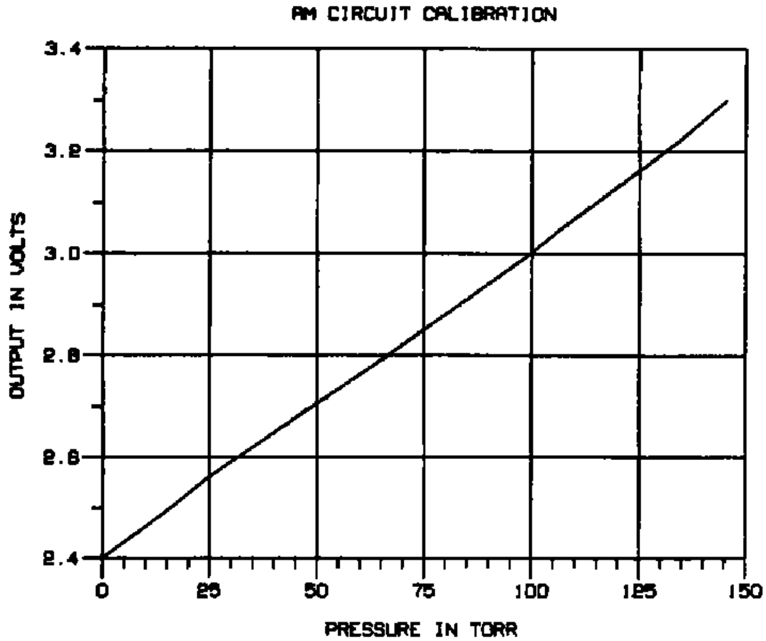


Figure 14. Static Calibration of the Capacitive Pressure Transducer Driven by the AM Circuit

The responsiveness of the resonant circuit is achieved by placing the driving frequency near the pole of the transfer function. For the LC circuit employed here the pole pair of the transfer function is found slightly to the left of the imaginary axis point $1/\sqrt{LC}$. Maximum responsiveness is achieved when the driving frequency gives an output 3dB below the resonant peak (Figure 13b). Over the pressure range of our measuring device a linear relationship to output voltage is achieved. Figure 14 shows the calibration curve obtained with the AM circuit. By comparing this result to Figure 9 the relationship of demodulated output voltage to capacitance variation can be obtained.

4.4 Dynamic Tests

Two series of experiments were conducted to determine the dynamic response of the pressure transducer, using the modified B & K Type 4136 cartridge as the primary sensor. These tests and their results are described below.

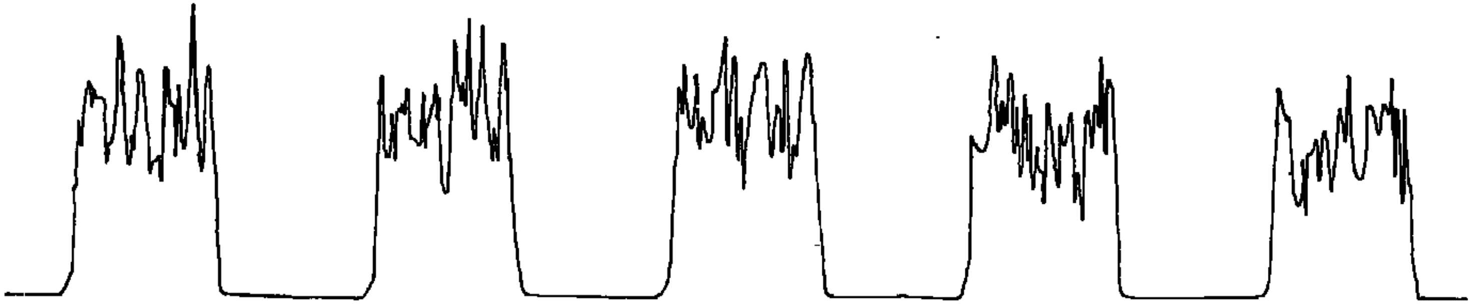
4.4.1 Determination of Rise Time

To determine the rise time of the primary sensor in response to a pressure pulse, a series of experiments was conducted using the dynamic test stand described in Section 3.3 (Figure 2). To calibrate the measurements, the same experiments were conducted using the Micro Switch pressure transducer (Section 3.6).

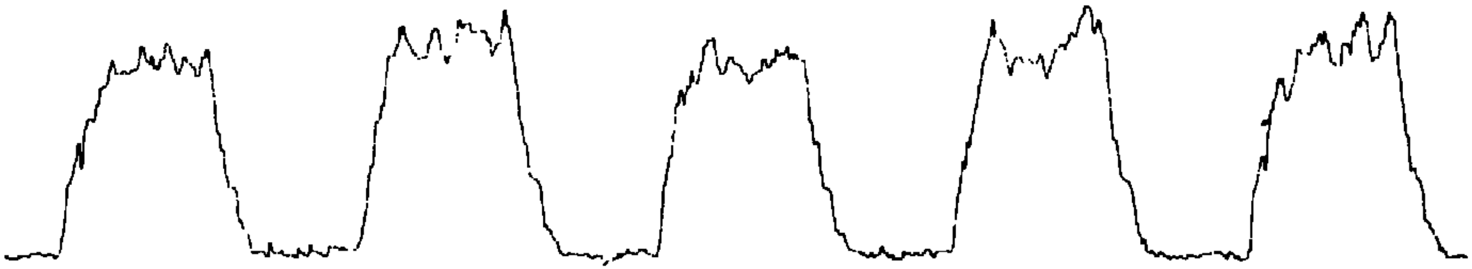
During the experiments, the high-pressure ports of the transducers were covered with an aluminum cap through which a 0.38-mm ventilation hole was drilled. This cap was used as a total pressure probe placed directly below the air jet. As the slot wheel rotates, the pressure transducer experiences a nearly square wave pressure pattern as it is cyclically exposed to the impinging air jet. The transient time of the on-off action is relatively short, depending on the size of the jet and the rotating speed of the slot wheel. The transient rise time may be estimated by dividing the air jet diameter by the circumferential speed of the slot wheel. For the present setup, the nozzle diameter is 0.12 cm and the transient rise time is estimated to be about 0.06 ms. Measurements of the rise time, using a Kistler piezoelectric transducer (Model 207/61) driven by a Kistler Piezotron Dual Mode Amplifier (Model 504E) with a system rise time of 1.5 μs, shows that the rise times of the pressure pattern of the setup are about 0.1 and 0.05 ms for rotating speeds of 4000 and 8000 rpm, respectively. The measured values are comparable with the above estimated value.

Figure 15 shows the results of the dynamic tests with the slot wheel rotating at about 4200 rpm. The ordinate is the output voltage, and the abscissa is the time. The signals measured with the Micro Switch and the capacitive pressure transducers are shown in Figure 15a and 15b, respectively. The signals were recorded on 5.25-in floppy disks using a Nicolet disk recorder (XF-44/1). Each record has a total of 16K data points, and the sampling time between points is 5 μs. Both signals show square-wave-like output, which corresponds to the on-off cycle impingement of the jet chopped by the rotating slot wheel.

From these signals, the rise time was estimated using a program furnished with the Nicolet digital oscilloscope (Series 4094). The program calculates the time and voltage difference between two points on the rising (or falling) slope of a waveform. The rise time is defined as the time between 10 and 90 percent of the maximum voltage difference. From three records, each containing



a. Response of the Micro Switch Transducer
Average Rise Time = 0.3 ms



b. Response of the Capacitive Transducer (B&K Type 4136)
Average Rise Time = 0.7 ms

Figure 15. Rise Times of Two Pressure Transducers –– The Pressure Pulses Correspond to the Total Pressure of an Impinging Jet Chopped by a Rotating Slot Wheel at 4200 rpm (Period = 7.12 ms)

10 waveforms, the rise time was estimated to be about 0.3 ms for the Micro Switch transducer and 0.7 ms for the capacitive transducer. This translates into a frequency response better than 1 kHz, well above the 200 Hz specified by DOD.

As a pressure transducer, the Micro Switch transducer has a maximum rise time of 1 ms, according to the manufacturer. The slower rise time of the capacitive transducer is due to the larger cavity inside the pressure ports between the capillary hole (on which the jet is impinging) and the sensing diaphragm. From the B & K data handbook (B & K, 1982) and the calibration chart of the individual cartridge, the resonance frequency of the Type 4136 cartridge is about 70 kHz, and the open circuit pressure response is flat up to at least 10 kHz. When used as a pressure transducer in the present configuration, the relatively large diameter of the B & K cartridge (0.6 cm) results in a larger cavity size and a more irregular cavity configuration than those of the Micro Switch transducer. The larger the size of the cavity, the more damping of the pressure signals is anticipated. The design of the cavity inside the pressure ports could be optimized to further increase the frequency response of the capacitive transducer.

4.4.2 Determination of Frequency Response

To determine the frequency response of the capacitive pressure transducer, a series of experiments were conducted using the pipe flow system described in Section 3.3 (Figure 3). A total of 9 screens and 1 perforated plate were used for most of the experiments. At 20 psi line pressure, the mean pressure drop across the screens and the plate was about 0.85 psi.

The outputs of the transducers were fed into the programmable signal conditioner (Datacon Electronics, Model PSC-16). The outputs from the signal conditioner were fed into a Data General minicomputer through an analog-to-digital board. Four channels were used to measure the pressure drop across the screens and perforated plates. The first and the last two channels were connected to the output terminals of the Micro Switch and capacitive transducers, respectively. Two different filters ranging from 50 to 1000 Hz were used for each of the two channels. Data were recorded at a sampling rate twice the higher filter setting for each run. This procedure was designed to remove aliasing for spectral analysis of the data.

Prior to each set of measurements, the two transducers were calibrated using a 5-psi diaphragm gauge (Section 3.6). For calibrations, the low pressure ports of the two transducers were disconnected from the pipe and then connected to each other. The two pressure tabs on the pipe located at the downstream side of the screens were then closed and connected with a Tygon tube. The valve at the downstream end of the pipe was closed during calibration. Calibration was accomplished by pressurizing the pipe at 0, 0.5, 1.0 and 1.5 psi. A second-degree polynomial was used to best fit the calibration data.

Figures 16 and 17 are two typical calibration curves for the Micro Switch transducer and the capacitive transducer under development. The abscissa and ordinate are the pressure in psi and the output voltage. The calibration measurements for the both transducers appear to be slightly nonlinear. Part of the nonlinearity is inherent to the diaphragm gauge, which is not a highly accurate instrument. Factory-furnished calibration of the Micro Switch transducer shows a linear trend in the calibration curve. In Phase II, FLOW proposes to acquire a precision pressure gauge for calibration of the transducers. Meanwhile, the electronic circuit will be optimized to achieve better linearity. With the incorporation of the microprocessor, linearization of the calibration may be easily achieved.

Figures 18 through 20 are time series of the measurements for three low pass filtration runs at 50, 100 and 500 Hz. The abscissa is the time in seconds and the ordinate is the pressure drop across the screens and perforated plate in pounds per square inch. The solid and dashed curves correspond to the signals simultaneously measured with the capacitive and Micro Switch transducers, respectively. The signals at 50 and 100 Hz are practically identical, with minor discrepancies likely attributed to the difference in the configuration and size of the cavities between the entrance of the pressure ports and the sensing elements, as discussed earlier.

At 500 Hz, noticeable discrepancies are observed between the two simultaneously recorded signals. It appears that the frequency response of the capacitive transducer is inadequate, resulting in a relatively low amplitude of the high-frequency components. It turns out, however, that this inadequate frequency response is caused by the small size of the ventilation hole of the B & K microphone cartridge, which is connected to the low pressure port of the transducer. For acoustic pressure measurements, the ventilation hole was

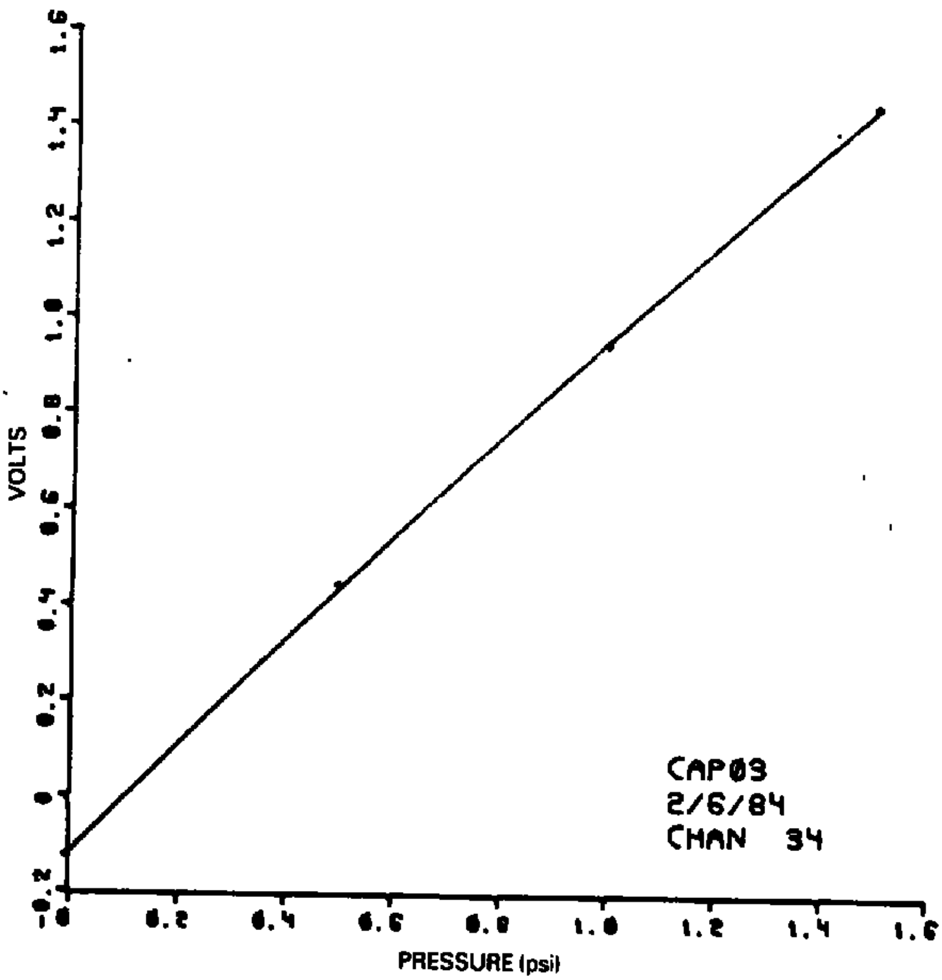


Figure 16. Calibration Curve for the Micro Switch Transducer (142PC05D)

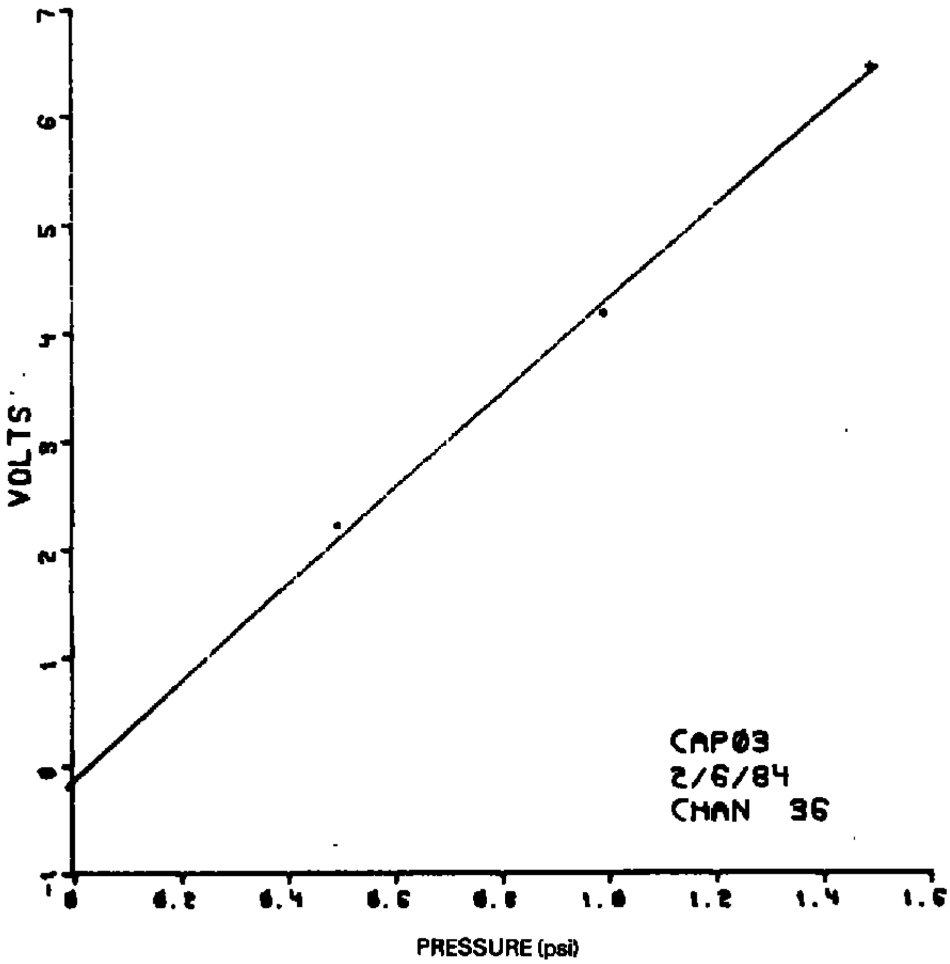


Figure 17. Calibration Curve for the Capacitive Transducer with a B&K Type 4136 Microphone Cartridge as the Primary Sensor

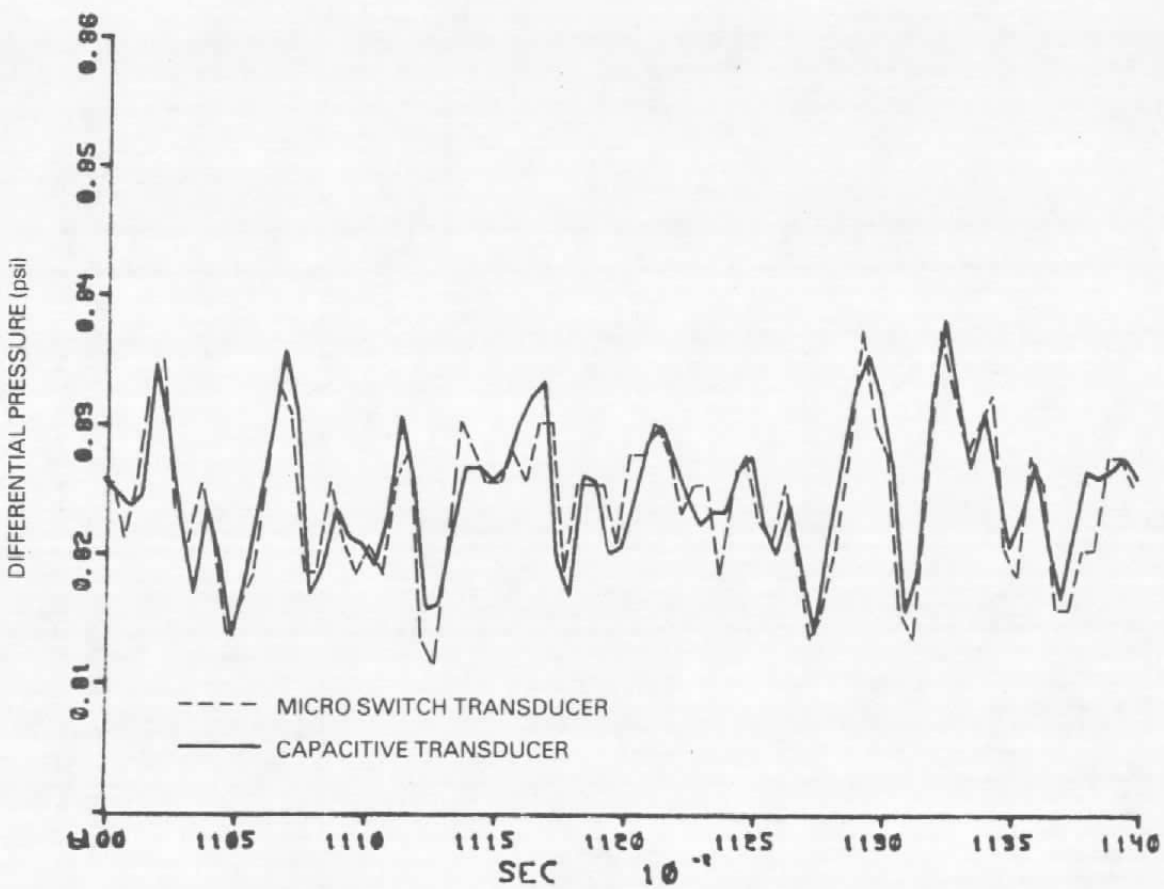


Figure 18. Comparison of Time Series Measured Simultaneously with Two Pressure Transducers —— Low-pass Filter = 50 Hz

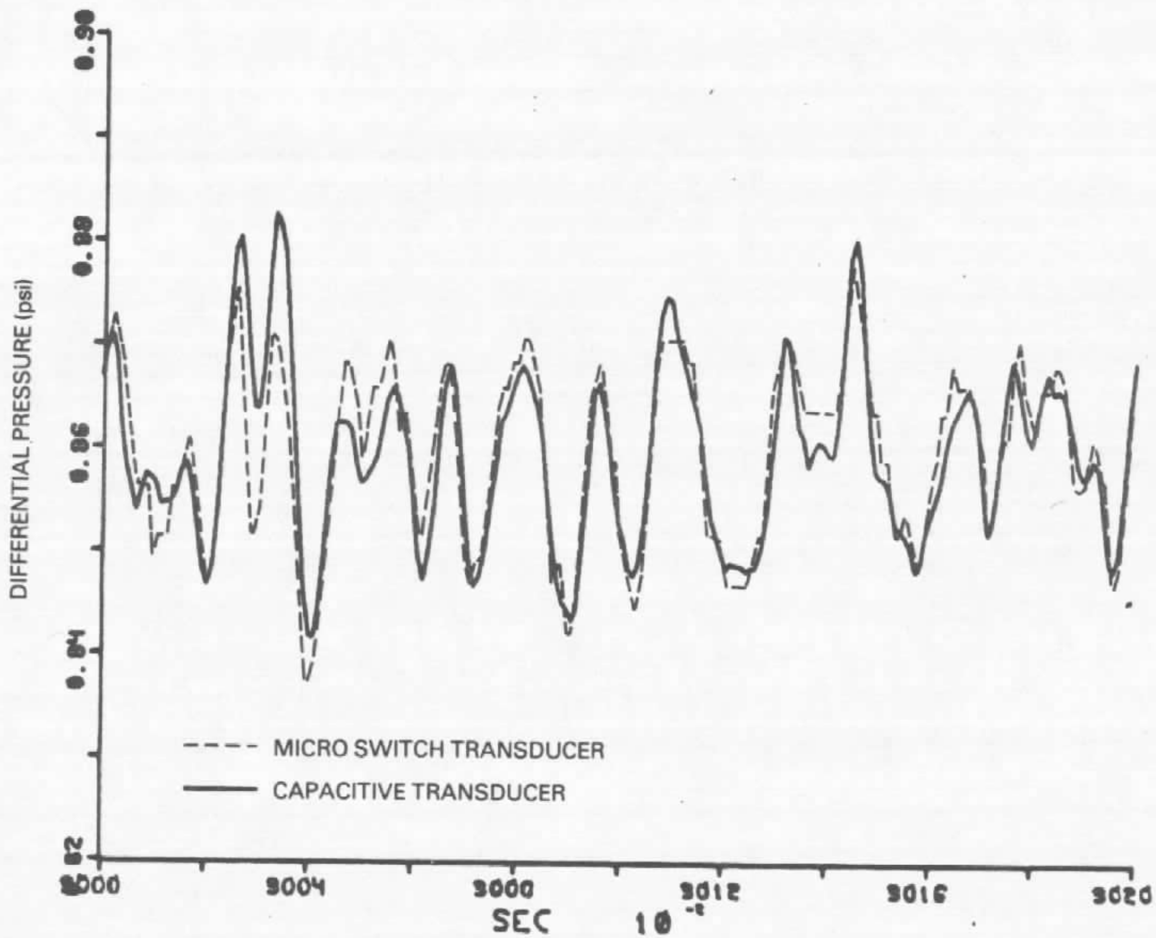


Figure 19. Comparison of Time Series Measured Simultaneously with Two Pressure Transducers —— Low-passs Filter = 100 Hz

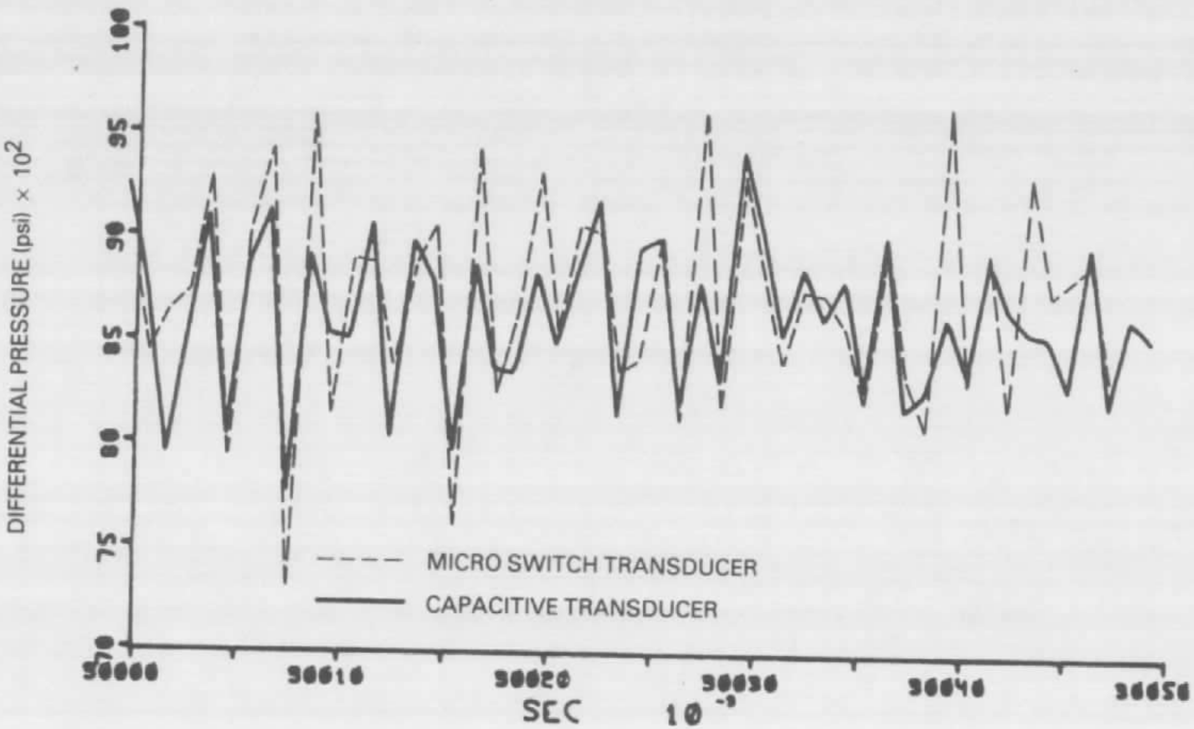


Figure 20. Comparison of Time Series Measured Simultaneously with Two Pressure Transducers —— Low-pass Filter = 500 Hz

specially designed to remove the dc components (B & K, 1983). The solution is simply to enlarge the ventilation hole. This will be done during Phase II, when modification or redesign of the primary sensor is considered and implemented.

To quantify the effect of the ventilation hole, the root-mean-square (rms) values and the spectra of the pressure signals are calculated. The ratio of the rms pressure fluctuations measured with the capacitive transducer to those measured with the Micro Switch transducer versus the low pass filtration is shown in Figure 21. The data spread is estimated to be ±5 percent, as indicated by an error bar on the figure. Below 100 Hz, the ratio is better than 0.95. The small discrepancy may be partially due to the difference in the size and configuration of the cavity inside the pressure ports of the transducer. The ratio drops gradually to about 0.8 at 500 Hz. From the fairing curve the ratio is better than 0.9 at 200 Hz.

Dynamic tests revealed a 0.7-ms rise time in the capacitive transducer with the present configuration. Therefore, it is anticipated that a frequency response better than 1000 Hz can be achieved simply by enlarging the ventilation hole. Further increase in the frequency response may be achieved by optimizing the configuration and size of the cavity inside the pressure ports, a task to be conducted in Phase II. The abscissa and ordinate are respectively the frequency in hertz and the spectral density. The spectra were calculated from the autocorrelation of the singlas via a fast Fourier transform scheme (Liu and Lin, 1982). The solid and dashed curves are the spectral density of the pressure signals measured with the capacitive and Micro Switch transducers, respectively. The error bars are the 95-percent confidence level of the spectral estimate. For a 50 Hz low-pass filtration, the pressure signals have practically no high frequency components. The two spectra are practically the same within the accuracy of the spectral analysis.

Below 0.2 Hz the rising spectral density is believed to be caused by the low frequency variations in the pressure source. For a 500 Hz low pass filtration, the two spectra compare favorably, except at the high frequency end where a noticeable discrepancy is observed. Beyond 300 Hz, the spectral density calculated from the signals of the Micro Switch transducer continues to rise, whereas that of the capacitive transducer drops rapidly. Again, the discrepancy is caused by the small ventilation hole in the B & K cartridge, which limits the frequency response of the capacitive transducer. A simple

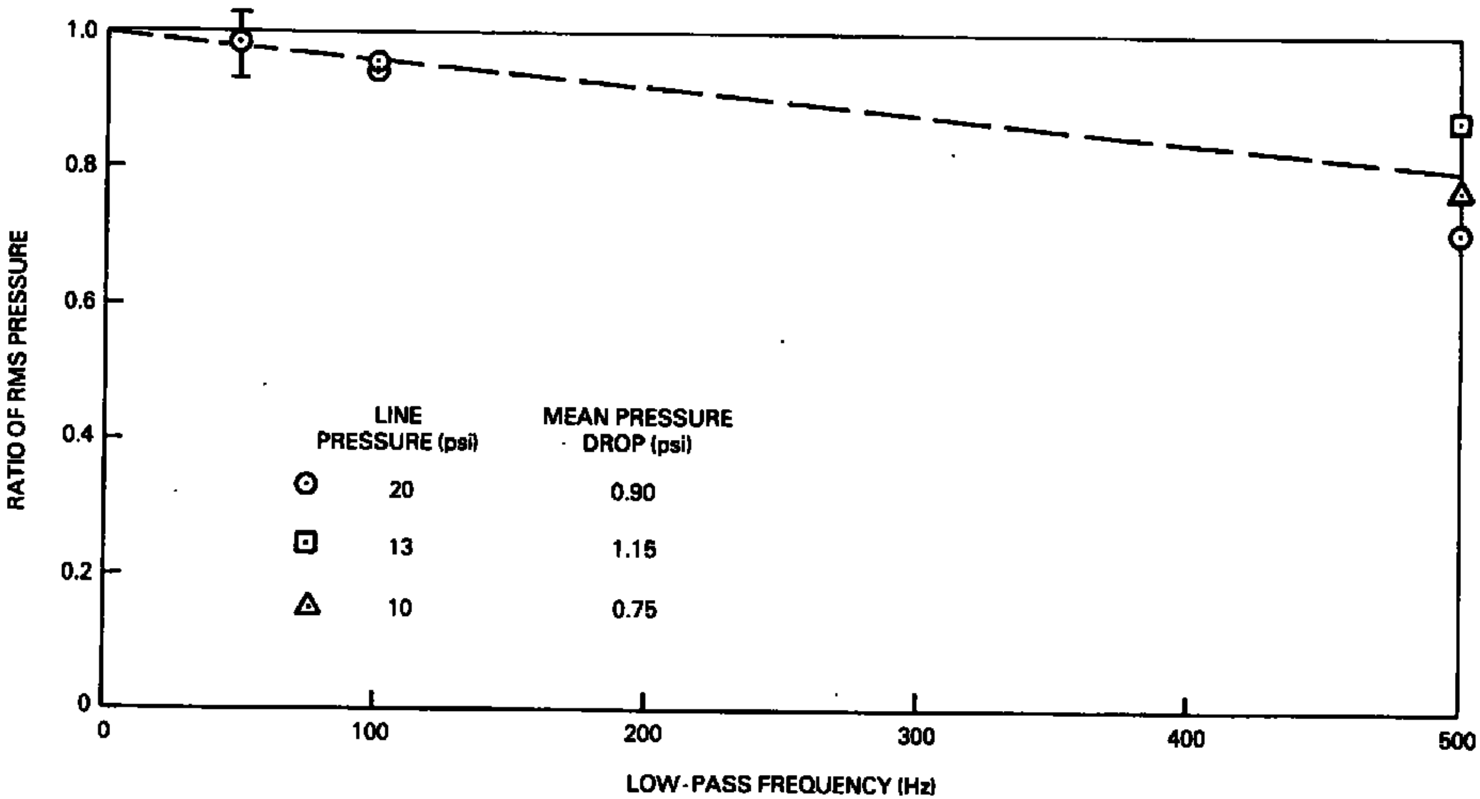


Figure 21. Ratio of RMS Pressure Measured with the Capacitive and Micro Switch Transducers

solution is to open up the ventilation hole, which may achieve a frequency response better than 1000 Hz as discussed above.

Note also, from Figures 22 and 23, that the spectra show a very narrow frequency range. This is because the openings of the screens and perforated plate are so small that only small eddies with high frequency contents are generated across the screen.

To further examine the performance of the capacitive transducer, the cross correlation and cross spectrum were calculated for the signals measured simultaneously with the two transducers. Figure 24 shows the coherence, phase and magnitude versus frequency, as derived from the cross spectrum. The figure demonstrates that the two signals are highly correlated up to 100 Hz, with coherence better than 0.8, zero phase shift and a constant magnitude. Beyond 100 Hz, the constancy of the coherence, the phase and the magnitude begin to deteriorate as the damping effect of the small ventilation hole on the B & K cartridge becomes progressively stronger with the increasing frequency. The cross spectrum at the high frequency end will be examined in greater detail during Phase II, after the ventilation hole is enlarged and the configuration and size of the pressure ports are optimized.

4.5 Determination of Environmental Effects

From the DOD specifications given in Section 2, the pressure transducer (especially the primary sensor) under development is expected to be operated in a severe environment of high temperature and vibration. This section examines the effects of the high temperature and vibration environment on the primary sensor and the electronic circuits, and the expected error due to these effects. Finally, potential means to reduce this error are recommended for Phase II research and development.

4.5.1 Temperature Effects

One of the criteria for selecting the B & K microphone cartridges as the primary sensor is their high temperature resistance and stability. The mechanical sensor components can be affected by temperature variations in three ways:

- Elongation or shrinkage of materials: Due to the small physical dimensions of the cartridge, temperature-induced dimensional variations are

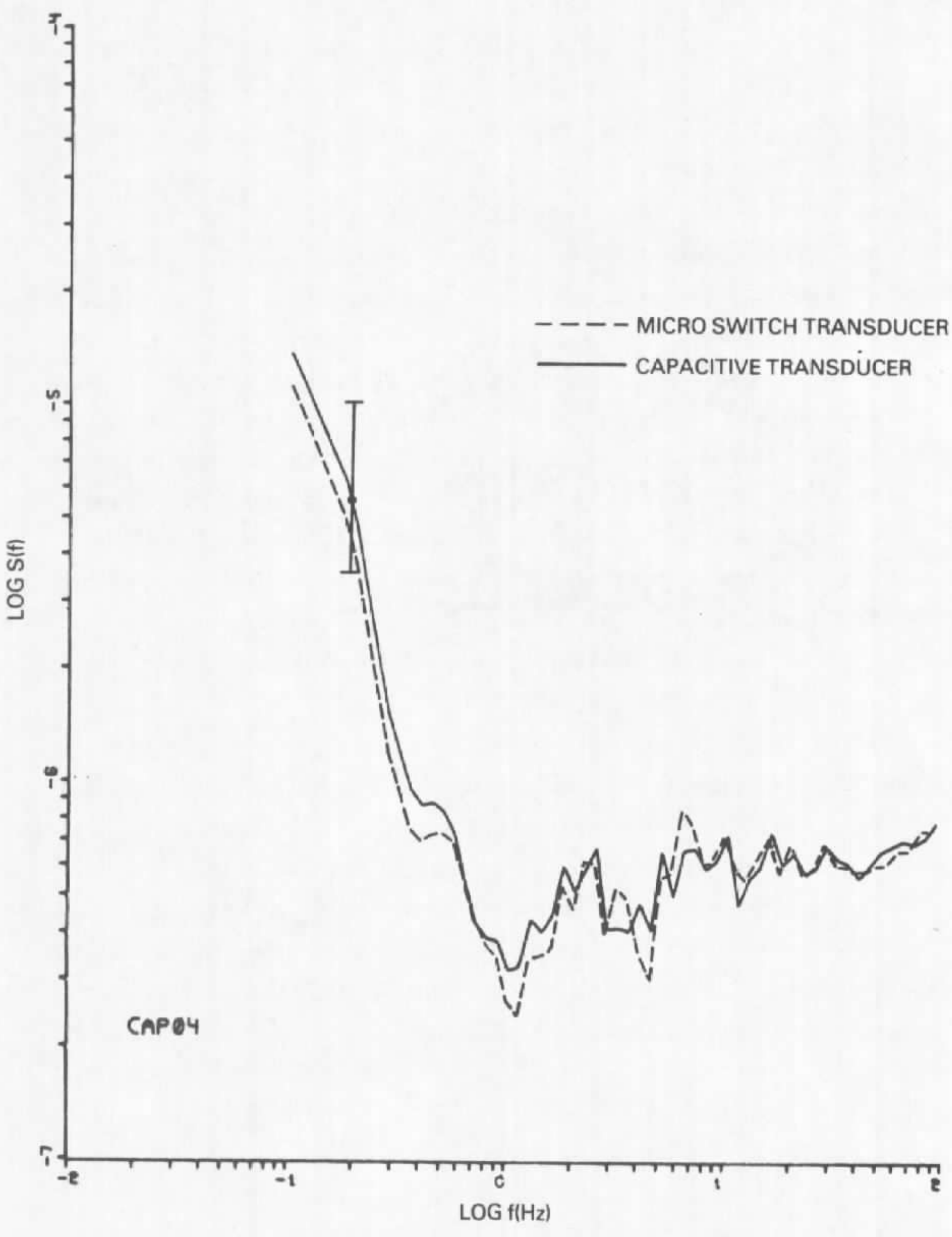


Figure 22. Frequency Spectra of the Pressure Fluctuation for the Capactive and Micro Switch Transducers — — Low-pass Filter = 50 Hz

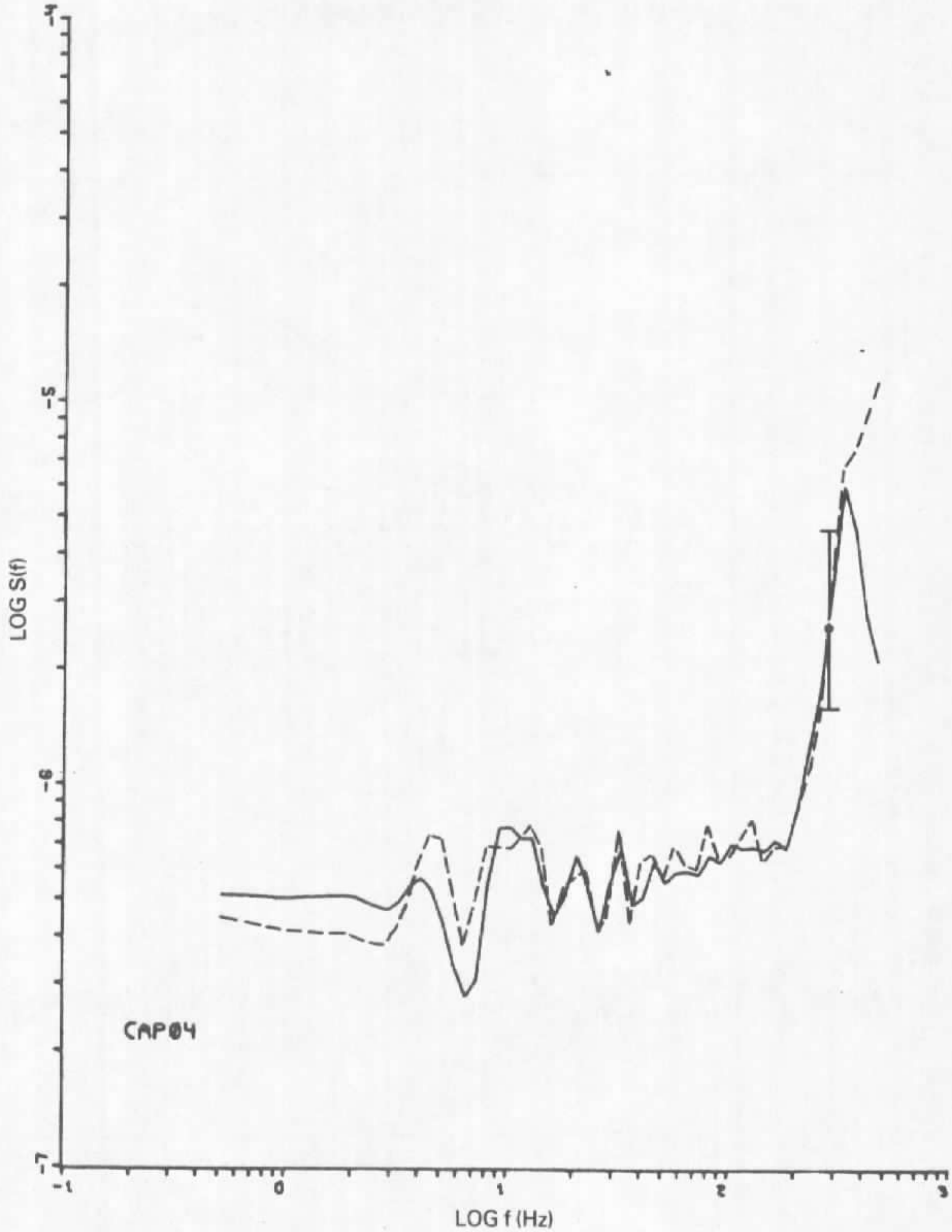


Figure 23. Frequency Spectra of the Pressure Fluctuation for the Capacitive and Micro Switch Transducers — — Low-pass Filter = 500 Hz

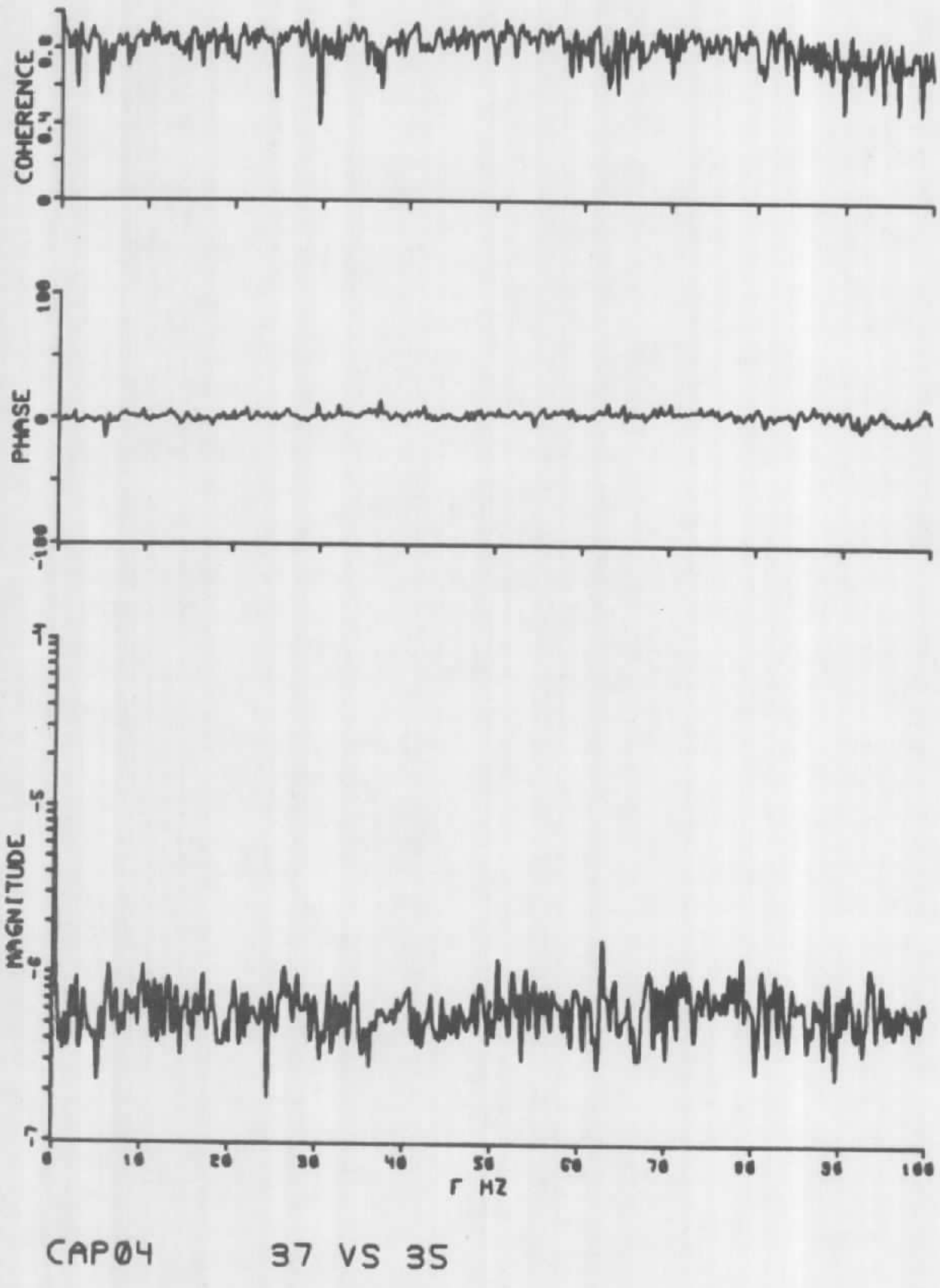


Figure 24. Coherence, Phase and Magnitude Derived from the Cross Spectra of the Pressure Fluctuations Measured with the Two Transducers

small. The cartridge was manufactured with care to match the temperature coefficients of the diaphragm and the supporting body, so this type of temperature effect is negligible.

- Variation of diaphragm prestress: The nickle diaphragm was prestressed at the time it was mounted onto the cartridge. The prestress stiffens the diaphragm. The completed cartridge has been subjected to a high-temperature (302°F) forced aging process to ensure long-term stability. It can be used continuously at temperatures between -58°F and 302°F, and intermittently at up to 392°F, though this is not recommended. Over a long period of time, especially when the cartridge is constantly exposed to high temperature, diaphragm creep relieves some of the prestress. The reduced diaphragm stiffness increases the sensitivity of the capacitive sensor. According to B & K (1982), the rate of change in the sensitivity is better than 1dB per 2 hours at 302°F. As seen in Figure 25 (taken from B & K, 1982, p. 83), the change of sensitivity at 225°F is better than 1 dB per 200 hours. At room temperature, the manufacturer claims stability on the order of 1 dB per thousand years. The reference pressure for the decibel definition is 20 μPa (2.9×10^{-9} psi). In the least favorable circumstances, the sensor will operate continuously at 225°F.
After 6.1×10^{7} hours (over 7000 years), the relative measurement error caused by temperature drift of the diaphragm can reach a maximum of 0.1 percent at 1 psi. Even under the worst conditions, recalibration of the sensitivity every six months will be more than adequate to ensure the accuracy for long-term operations. For applications in extremely high temperatures, however, it is advisable to protect the sensor by using water jackets or other passive devices.

- Variation of sensor capacitance: The capacitance between two parallel plates is given by Equation (1). For air, the relative dielectric constant is 1.0006, i.e., almost identical to that of a vacuum, and the influence of temperature on the dielectric constant is negligible.

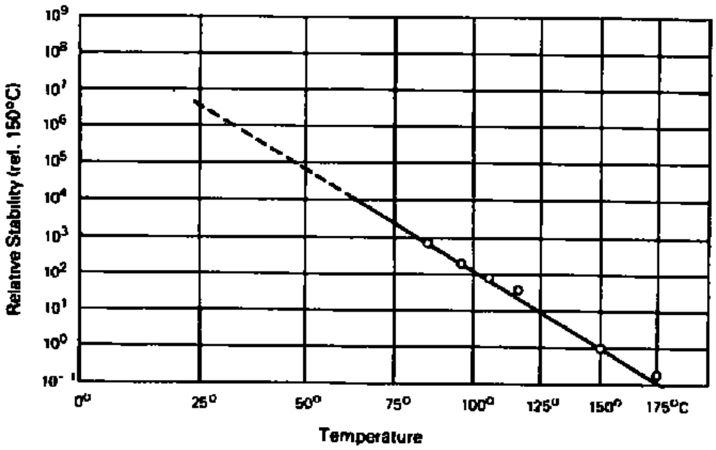


Figure 25. Long-Term Variation of Capacitive Sensor Sensitivity with Ambient Temperature (B&K, 1982)

The fixed capacitor plate is mounted onto a thick quartz plate (see Figure 6). The dielectric constant of fused quartz is independent of temperature up to about 200°C. Therefore, no steady state distortions of the pressure measurement by varying temperatures are predicted. This is also confirmed by the manufacturer's data on temperature drift (B & K, 1982, Figure 6.72), which in essence show only minimal temperature influence in the range from -40 to 220°C. The above results are given for acoustic measurements.

4.5.2 Temperature Tests

To identify any potential temperature effect on the variation of sensor capacitance, the capacitive sensor was placed into the test oven and tested for sensitivity to temperature variations in a range from 70 to 212°F. The oven temperature was set in increments of 10°C and each voltage signal at the FM output terminal was recorded after one hour to avoid errors from transient temperature effects. With the exception of the transient effects described below, the oscillator frequency remained constant over the duration of the experiments, indicating no change of capacitance within the temperature range from room temperature (20°C) to 100°C.

The system response to temperature transients was recorded by directing a high temperature air flow from a electric blower into the sensor. The microphone cartridge temperature was monitored by a copper-constantan thermocouple mounted onto the outside of the cartridge. A typical response curve is given in Figure 26 for a temperature step from 20°C to 110°C: the FM oscillator frequency increases slightly at first, then decreases slowly to the original frequency level. The maximum increase of frequency is 2.3 kHz, it occurs after 20 seconds and corresponds to a pressure signal of approximately 11.5 torr. For smaller or more gradual temperature changes this transient phenomenon is proportionally smaller. After one minute, the transient frequency increase is reduced to 0.5 kHz, corresponding to an error signal of 2.5 torr or 0.048 psi. After three minutes the error is below 0.01 psi or below 1% when referenced versus a 1 psi signal. It is important to emphasize that the values given here reflect a very large (40°C) and sudden temperature change without thermal insulation of the cartridge. When the cartridge was heated gradually in the oven for the static experiments, the transient effect was not measurable.

The transient effect can be explained by looking again at the geometry of the capacitor cartridge (see Figure 6). When being suddenly exposed to high

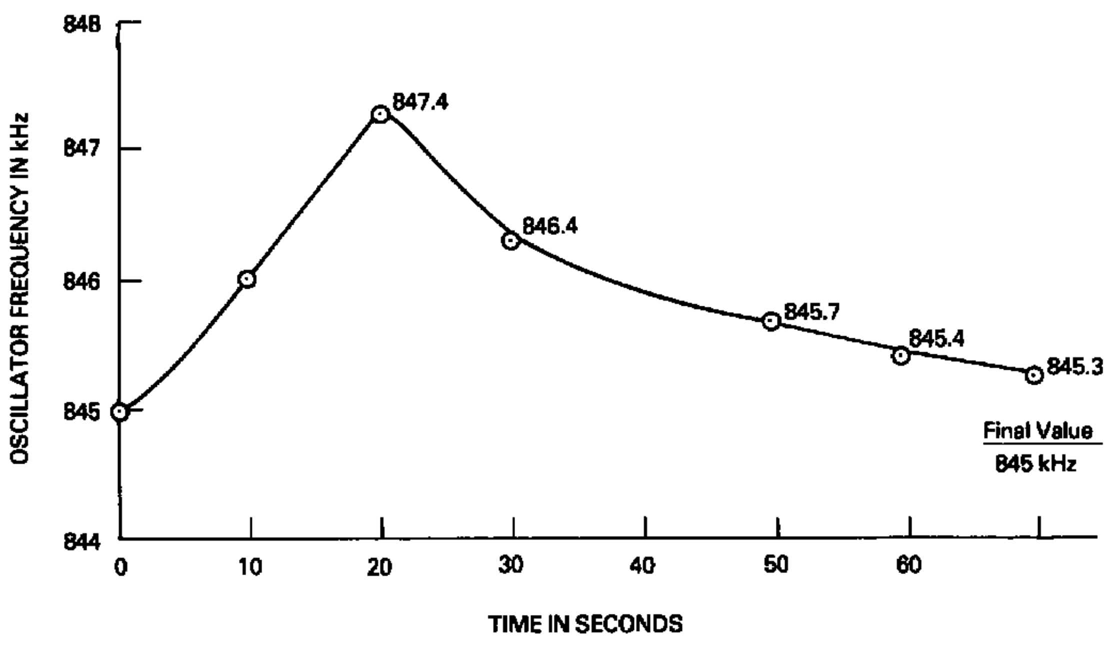


Figure 26. Transient Response of the Capacitive Sensor Oscillator Frequency to a Temperature Step Input from 20°C to 110°C

temperatures, the outer parts of the cartridge expand, increasing the gap between the two capacitive plates and increasing the oscillator frequency (the FM oscillator frequency increases with decreasing capacitance). As the higher temperature reaches the inner parts of the cartridge, the original gap and its corresponding oscillator frequency are gradually restored.

4.5.3 Vibration Effects

Vibrations that are transmitted to the diaphragm cause deflections and thus create an error. The magnitude of the error is determined by the orientation of the vibrational accelerations and the effective mass of the oscillating diaphragm.

Accelerations perpendicular to the diaphragm cause the largest deflections, whereas accelerations in the radial direction have no influence. If a preferred orientation of the vibrations exists, the larger errors will be avoided by orienting the diaphragm normal to the axis of maximum acceleration.

The diaphragm of the Type 4136 cartridge is 5 μm thick with an effective diameter of 4 mm, resulting in a total effective mass of about 0.03 mg. Using the theory discussed in Section 2, the maximum allowable acceleration for a 0.9-percent error margin is about 103 G. Considering the uncertainties in determining the dimensions of the diaphragm, this allowable acceleration is consistent with the manufacturer's experimental data for an average Type 4136 cartridge, tabulated in B & K (1982, p. 93). Here, the sensitivity to vibration is stated as 69 dB for 1 m/s^2 acceleration, where 0 dB corresponds to 20 μPa (2.9×10^{-9} psi). An acceleration of 10 G would thus create a pressure signal of about 109 dB or 5.6 Pa (0.81×10^{-4} psi). The 0.9-percent accuracy limit (at 1 psi signal) is specified at 0.009 psi (6.2 Pa) or 130 dB, which is reached by an acceleration of 111 G. Further reduction in the effect of vibration may be achieved by the provision of isolation mounts to the primary sensor, bringing the relative error down to about 10^{-5} at 10 G.

For the electronic circuit, the effect of vibration is anticipated to be insignificant because it will be physically separate from the primary sensor. Adequate vibrational isolation may be achieved by using flexible connectors between the primary sensor and the circuit.

4.5.4 Vibration Tests

Using the test stand described in Section 3.4, the sensitivity of the capacitive sensor to vibrations was tested. During all tests, the diaphragm was oriented normal to the direction of vibrations, generating the maximum possible error signal. As predicted, the influence of vibrations is generally quite small. The vibration tests were conducted at frequencies between 100 and 200 Hz, with variations of acceleration from 0 to 10 G r.m.s. However, the measurement results of both the accelerometer and the pressure sensor did not depend on the vibration frequency. The results given below were recorded at 200 Hz. The acceleration level was measured with the piezo-accelerometer described in Section 3.4. The capacitive transducer output voltage (using the AM-circuit) was passed through a bandpass filter to eliminate line interference, and then measured with a Tektronix Type 5110 oscilloscope.

As the acceleration increases, the capacitive transducer output signal increases proportionally, oscillating in a sinusoidal waveform proportional to the shaker motion. At an acceleration of 10 G rms, a capacitive transducer signal of 0.4 mV rms was measured. The measurement uncertainty of this result is high because an unshielded extension line had to be installed between the capacitive transducer and the oscillator/demodulator unit (a shielded line would have more than doubled the stray capacitance). The unshielded line generated a random noise level of about 0.2 mV rms and line noise which was filtered out with a bandpass filter set at 200 Hz. Using the calibration curve in Figure 14, the signal at 10 G rms corresponds to a pressure of 0.08 torr or 1.4×10^{-4} psi, generating a relative error of .14% at 1 psi pressure level and 10 G rms acceleration. The theoretically predicted signal (Section 4.5.3) for 10 G is 0.81×10^{-4} psi. The higher experimental value is presumed to be caused mainly by the low signal-to-noise ratio of the breadboard circuit used in the vibration test. Significant reduction in the signal-to-noise ratio and thus the above errors will be achieved in the prototype transducer assembly to be built in Phase II. Note that the above errors are the maximum errors that can be significantly reduced by the provision of isolation mounts and by mounting the primary sensor perpendicular to the axis of the vibrational motion (Section 4.5.3).

5. CONCLUSIONS AND RECOMMENDATIONS

During the Phase I study, FLOW successfully demonstrated the feasibility of developing a capacitive pressure transducer for measuring differential pressure in high-temperature and vibration environments. Test results strongly indicate that, with proper modifications of the primary sensor (B & K Type 4136 microphone cartridge or an equivalent product) and further research and development to be performed in Phase II, it is possible to develop a prototype transducer that meets all DOD requirements. The most important findings supporting the successful demonstration of the feasibility are summarized below:

- A primary sensor selected for the transducer assembly is a B & K Type 4136 microphone cartridge, which surpasses most of the DOD requirements (see Table 1 and Section 4.1). With proper modifications of the cartridge for accomodation of differential pressure measurements and high line pressure, the primary sensor will surpass all the DOD requirements by a wide margin.

- Two different oscillator/demodulator circuits, one uses frequency modulation and the other amplitude modulation, have been developed and tested. Both circuits work well in a constant-temperature environment. At elevated temperatures, however, the AM circuit is expected to perform better than the FM circuit due to the superior temperature stability of its crystal-controlled oscillator (Section 4.3.2). In Phase II, the AM circuit will be optimized for the prototype transducer assembly.

- Experimental results of the dynamic tests show that the rise time of the capacitive transducer is about 0.7 ms (Section 4.4.1). This rise time may be potentially reduced by optimizing the design of the cavity inside the pressure ports because the B & K diaphragm has a much higher resonant frequency of 70 kHz.

- Differential pressure measurements were conducted in a pipe flow system, which was designed to simulate the conditions across the screen in the inlet plenum of the T-1 cell, using the capacitive transducer and a

Micro Switch transducer as a calibrator having a rise time better than 1 ms. Comparison of the data measured simultaneously has demonstrated that results of the capacitive transducer agree well with those of the Micro Switch transducer for frequency up to 100 Hz. Noticeable discrepancy begins to show for pressure signals beyond 300 Hz. The discrepancy is mainly due to the inadequate ventilation hole (on the B & K cartridge) connecting to the low pressure port. This can be corrected simply by enlarging the ventilation hole, one of the modifications to be made in Phase II.

- The capacitive transducer was tested for sensitivity to vibrations and temperature variations. The experiments essentially confirmed the theoretical predictions for the sensitivity to vibrations, allowing accelerations up to 100 G and beyond at less than 1% error. The B & K cartridge proved to be temperature sensitive for fast temperature variations. When a step temperature change occurs, an error signal is produced for a short time. The magnitude of the error depends on the step magnitude and on the amount of thermal insulation provided to the capacitive cartridge. It is assumed that the geometrical conditions at the location of the sensor installation will allow for sufficient thermal insulation of the sensor so that the transient thermal effect will be negligible.

From the above findings, we have incorporated all the necessary modifications of the primary sensor and the housings in a new design, as illustrated in Figure 27. A detailed description of all the elements in the figure has been given in the Phase II proposal (Flow Industries TP-8465) submitted to AEDC for review and approval. Recommendations for Phase II research and development used on the Phase I findings have been presented in the work plan of the proposal (Section 5). At the completion of Phase II, we are confident that a self-contained, microprocessor-controlled prototype transducer will be completed and successfully tested in the AEDC Engine Test Facility. The prototype transducer, which will at least meet all the DOD requirements, will find a wide range of applications not limited to the intended measurements.

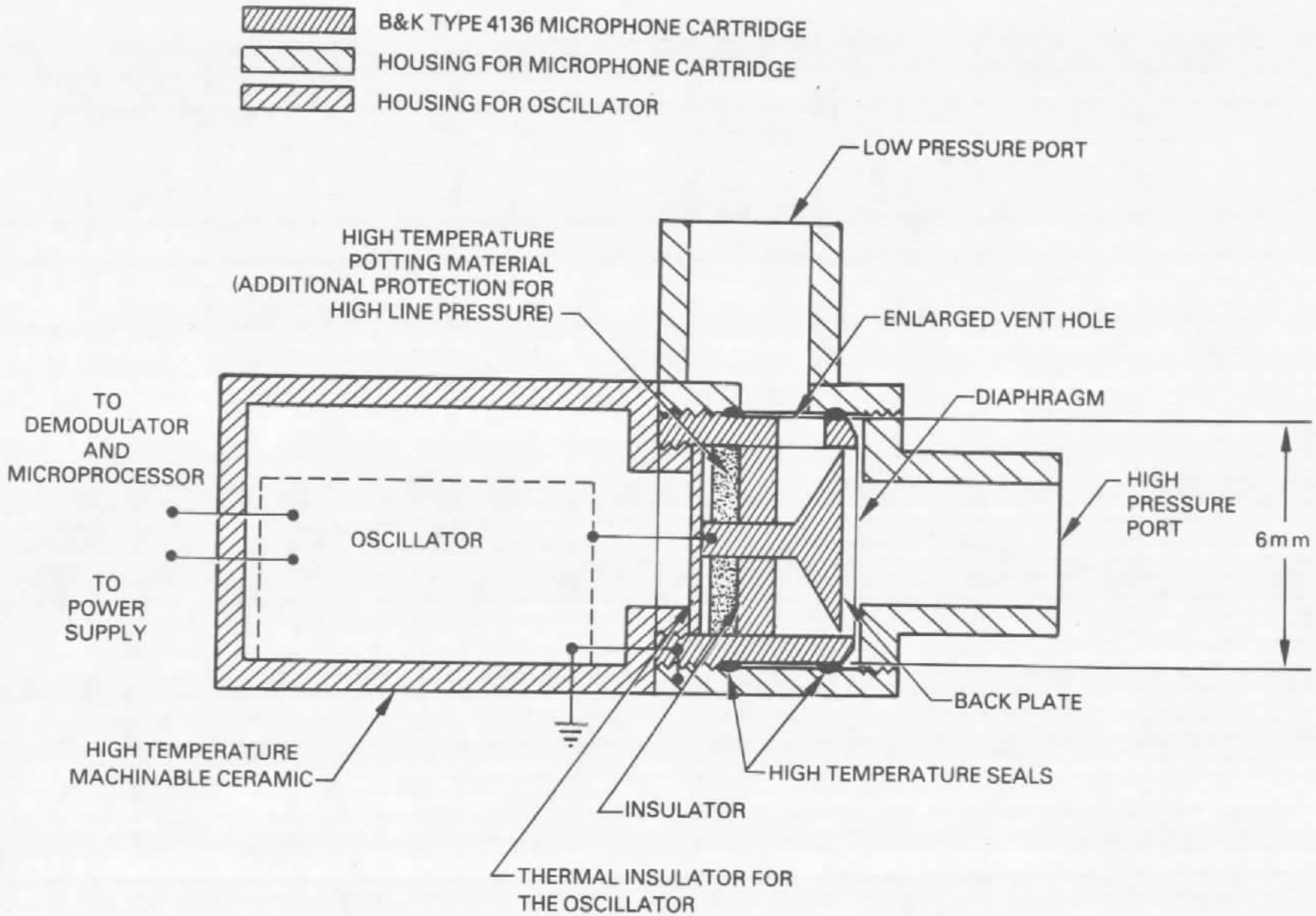


Figure 27. Schematic Construction of a Revised Pressure Transducer

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